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THE 2004 INDIAN OCEAN TSUNAMI IN THE MALDIVES: SCALE OF THE DISASTER AND TOPOGRAPHIC EFFECTS ON ATOLL REEFS AND ISLANDS

HIRONOBU KAN, MOHAMED ALI, AND MAHMOOD RIYAZ

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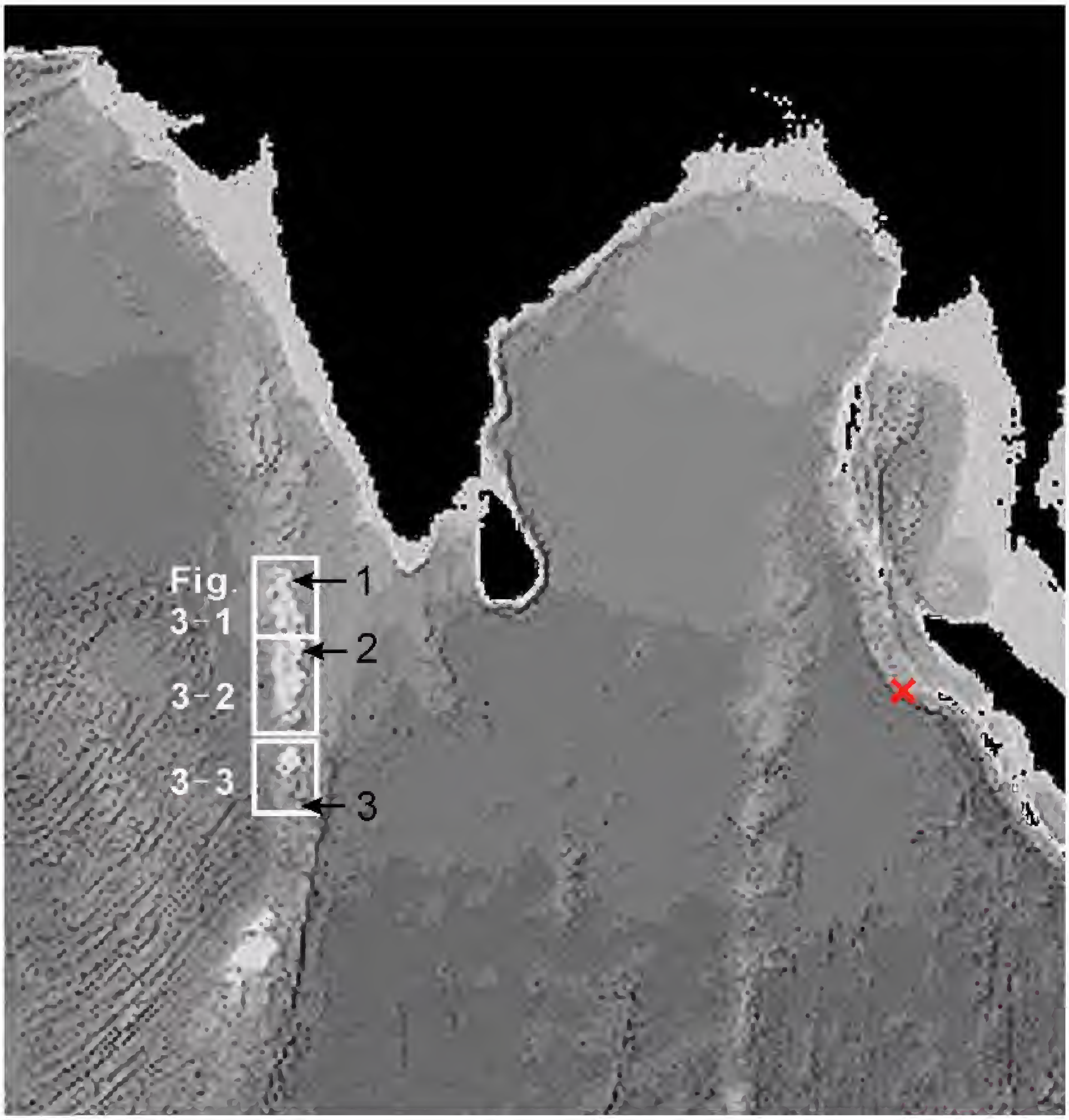

Figure 1. Maldive Islands (white boxes: see Figure 3-1, 3-2 and 3-3 for detail) and the epicenter (red cross) of the Sumatra Earthquake in December 2004. Arrows show the tide-observation sites (1: Hanimaadhoo; 2: Hulhumalé; 3: Gan).

THE 2004 INDIAN OCEAN TSUNAMI IN THE MALDIVES: SCALE OF THE DISASTER AND TOPOGRAPHIC EFFECTS ON ATOLL REEFS AND ISLANDS

BY

HIRONOBU KAN,[1] MOHAMED ALI,[2] AND MAHMOOD RIYAZ[3,4]

ABSTRACT

Following the tsunami caused by the Sumatra-Andaman earthquake of 26 December 2004, the Republic of Maldives reported 82 confirmed deaths, 26 people missing and more than 3,997 incidents of house/building damage. Such an experience suggests that all atoll nations/districts in the Pacific and Indian Oceans face a potential risk of severe tsunami-induced damage, and an understanding of what occurred may help us to form a basis for recognizing the safer areas of land on atoll islands.

To this end, we investigated 43 islands in the northern-to-southern Maldives by measuring watermarks and profiles across the islands, and interviewing local residents to determine the characteristics of the tsunami and evacuation procedures.

The movement and influence of the tsunami varied by atoll and island topography. In the northern Maldives where the atoll rims consist of numerous faroes and are interrupted by many channels, the tsunami entered the lagoons through these channels and appeared to set-up the lagoon water level. The backwash of the lagoon water to the open ocean caused inundation of the lagoon-side villages on islands at the eastern atoll rim. Beach ridges developed on the eastern side of these islands acted as breakwaters against the tsunami from the east. In contrast, catastrophic damage and high run-up levels of 3.6 m above Mean Sea Level (MSL) at maximum water depth occurred on the eastern islands in atolls with a continuous atoll rim in the southern Maldives. Damage on the western atoll rims and in the lagoons was relatively small. The continuous eastern atoll rim and its islands acted as a breakwater against the tsunami from the east. The eastern islands in atolls in the central Maldives where the atoll rim is moderately interrupted by channels were hit by both the direct surge from the east and floodwater from the lagoon. Less damage was reported from the far southern atolls where major channels cut across the atoll chain.

The movement of the tsunami in atolls thus differed according to the distribution of the atolls in the archipelago and the continuity of atoll rims against the incoming direction of the tsunami. The disaster status on individual islands also differed according

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[1]Laboratory of Physical Geography, Faculty of Education, Okayama University, 3-1-1 Tsushima-Naka, Okayama 700-8530, Japan. email: kan@cc.okayama-u.ac.jp
[2]SAARC Coastal Zone Management Centre, Jamaaludheen Building, Malé, Republic of Maldives
[3]Environment Research Centre, Jamaaludheen Building, Malé, Republic of Maldives
[4]Geotechnical and Geoenvironmental Engineering, School of Engineering and Technology, Asian Institute of Technology, P.O. Box 4 Klong Luang, Pathumthani 12120, Thailand

to the location of islands on atolls, height of islands, and development of beach ridges and associated topographic zones.

It is generally understood that the Indian Ocean tsunami arrived without any forerunning phenomena in areas located west of tsunami source area. However, according to the results of our interviews in the southern Maldives, the following forerunning phenomena were in fact observed: 1) loud noises (from 2-to-10 minutes before the tsunami); 2) bubbling reef flat water (from 2-to-10 minutes before the tsunami); and 3) the thrusting up of house floors or the bottoms of concrete wells (a few-to-10 seconds before the maximum tsunami surge). Refuge taken in branched trees and in the lee of strong walls was especially effective on low-lying atoll islands. Fishing boats (dhonis) played an important role in the rescue of people swept into lagoons. It is hoped that the collation of detailed information on the December 2004 tsunami events and disaster measures taken in this report will contribute to a better understanding of the risks faced by atoll nations, as well as to risk management development.

INTRODUCTION

A giant earthquake of moment magnitude 9.1-to-9.3 occurred at 0:58:53 (GMT) on 26 December, 2004 off northwestern Sumatra with a focal depth of 30 km. The earthquake resulted from the Indo-Australian plate plunging northeastward beneath the southeastern Eurasian plate. This slip caused the Andaman Islands to move 4-to-7 m toward southern India (Bilham, 2005; Satake, 2005). A slow rupture around the epicenter expanded at a speed of 2-to-3 km per second toward the NNW, extending 1,200-to-1,300 km along the Andaman trough (Ammon et al., 2005). The series of ruptures lasted for about 8 minutes, with a long rupture inducing the giant earthquake and expanding the tsunami source area for 600-to-800 km NNW from the epicenter (Sieh, 2005; Stein and Okal, 2005; Ni et al., 2005; Lay et al., 2005; Krüger and Ohrnberger, 2005; Ishii et al., 2005). Shifts in the sea floor displaced more than 30 km^3 of seawater, generating a tsunami with principal wave period of about 30 minutes and raising global sea level by about 0.1 mm (Bilham, 2005; Lay et al., 2005). The tsunami caused massive loss of life; up to 300,000 died around the Indian Ocean (McCloskey et al., 2005).

The tsunami hit the Maldive Islands (Fig.1) 2,300 km west of the epicenter, about three hours after the earthquake. The leading edge of the tsunami propagated around 700 km per hour toward the west due to the abyssal depth between the Sunda trench and the Maldive Islands. More than one-fourth of the inhabited islands suffered severe damage to infrastructure and one-third of the citizens were affected in the Maldives (UNEP, 2005).

The accumulation of data regarding tsunami behavior on atolls is still limited. This study reports not only tsunami behavior but also the scale of the disaster on the atolls and atoll islands in the Maldives archipelago, based on our field research carried out between February and August 2005 of island topography, run-up height and disaster status for 43 islands from the northern-to-the-southern Maldive Islands. This study also provides geomorphological profiles of an extensive area of the Maldives which we believe will be of value to further atoll research.

OVERVIEW OF THE MALDIVES

The Maldive archipelago, located in the middle of the Indian Ocean at 7°7' N to 0°42' S, and 72°33' to 73°46' E, consists of approximately 1,200 coral islands on atolls aligned from north-to-south. The islands form an atoll chain at the northern end and southern end and a double atoll chain from 2°40' to 6° N. Of the 990 islands with some vegetation, 200 are inhabited (at the time of the 2000 census). The administrative system of the Republic of Maldives is organized hierarchically; there is the central government, 20 administrative districts (19 administrative atolls and the capital Malé) and the administration of each island.

The basement of the Maldives, a part of the Laccadives-Chagos Ridge, is late Palaeocene lava from the Reunion mantle plume that filled the tectonic depression created when the plates pulled away from each other. The onset of the Maldive carbonate system occurred in the early Eocene along with the northward movement of the Indian plate. The thickness of carbonate is confirmed at 2,106 m in the lagoon of North Malé Atoll and 3,315 m between South Malé and Ari Atolls (Purdy and Bertram, 1993; Aubert and Droxler, 1996).

A characteristic topographic feature of Maldivian coral reefs is the faro (Gardiner 1931), a term that derives from *faru*, meaning "coral reef" in Dhivehi. The faro is a ring-shaped reef (miniature atoll) with a diameter of tens-to-hundreds of meters. The depth of faro lagoons ranges from 2-to-3 m at shallowest to 20-to-30 m at deepest. According to Kench et al. (2005) and Kench (2006), who made numerous shallow drills on three islands in Baa Atoll, the formation of cays started around 5,500 to 4,500 calibrated years BP in faro lagoons and formed the present outline by 4,000 calibrated years BP.

Reef topography differs from north-to-south, with atoll rims consisting of many isolated faroes in the north and encircled atolls with a continuous rim dominating in the south, where the number of faroes gradually decreases. There are no faroes in the southernmost Seenu (Addu) Atoll. Lagoon depth gradually increases to the south at around 30-to-40 m in the northern Maldives, 40-to-60 m in the central Maldives, and 60-to-80 m in the southern Maldives (Stoddart, 1973; Risk and Sluka, 2000).

The mean annual rainfall increases in the south (Stoddart 1971). Larger rainfall events in the southern Maldives are considered to have increased karst erosion in the glacial period, deepening the atoll lagoon in the southern archipelago (Woodroffe 1992, Purdy and Bertram 1993).

The northeast monsoon is dominant in the dry season from December-to-March while the southwest monsoon is dominant in the wet season from April-to-November. The two seasons change gradually, and heavy rain, strong winds and severe storms are known to occur during the wet season. The southernmost Seenu (Addu) Atoll is located outside the monsoon belt (Risk and Sluka, 2000). Cyclones occur only rarely in the Maldives; the devastating effects of cyclones in 1896 and 1898 were described by Gardiner in 1903 (Woodroffe, 1992). High waves were last reported to have seriously affected the entire Maldives archipelago on April 10-12, 1987. Although storms like these are rare in the Maldives, the frequency of storms increases in the northern archipelago contributing to the development of rubble ramparts on reefs and on beach ridges on islands (Woodroffe, 1992).

OVERVIEW OF THE INDIAN OCEAN TSUNAMI IN THE MALDIVES

Tide Gauge Observation

The tide level data of the Maldives are stored in the database of the University of Hawaii's Sea Level Center (http://uhslc.soest.hawaii.edu) and are taken from three tide gauges stations at Hanimaadhoo in Haa Dhaalu Atoll, Hulhumalé in Kaafu Atoll and Gan in Seenu Atoll (Fig. 2). Tide level is recorded every 4 minutes. The maximum tsunami tide level was 182.6 cm above MSL at 9:40 (local time) in Hanimaadhoo, 142.0 cm at 9:24 in Hulhumalé, and 79.5 cm at 9:32 in Gan.

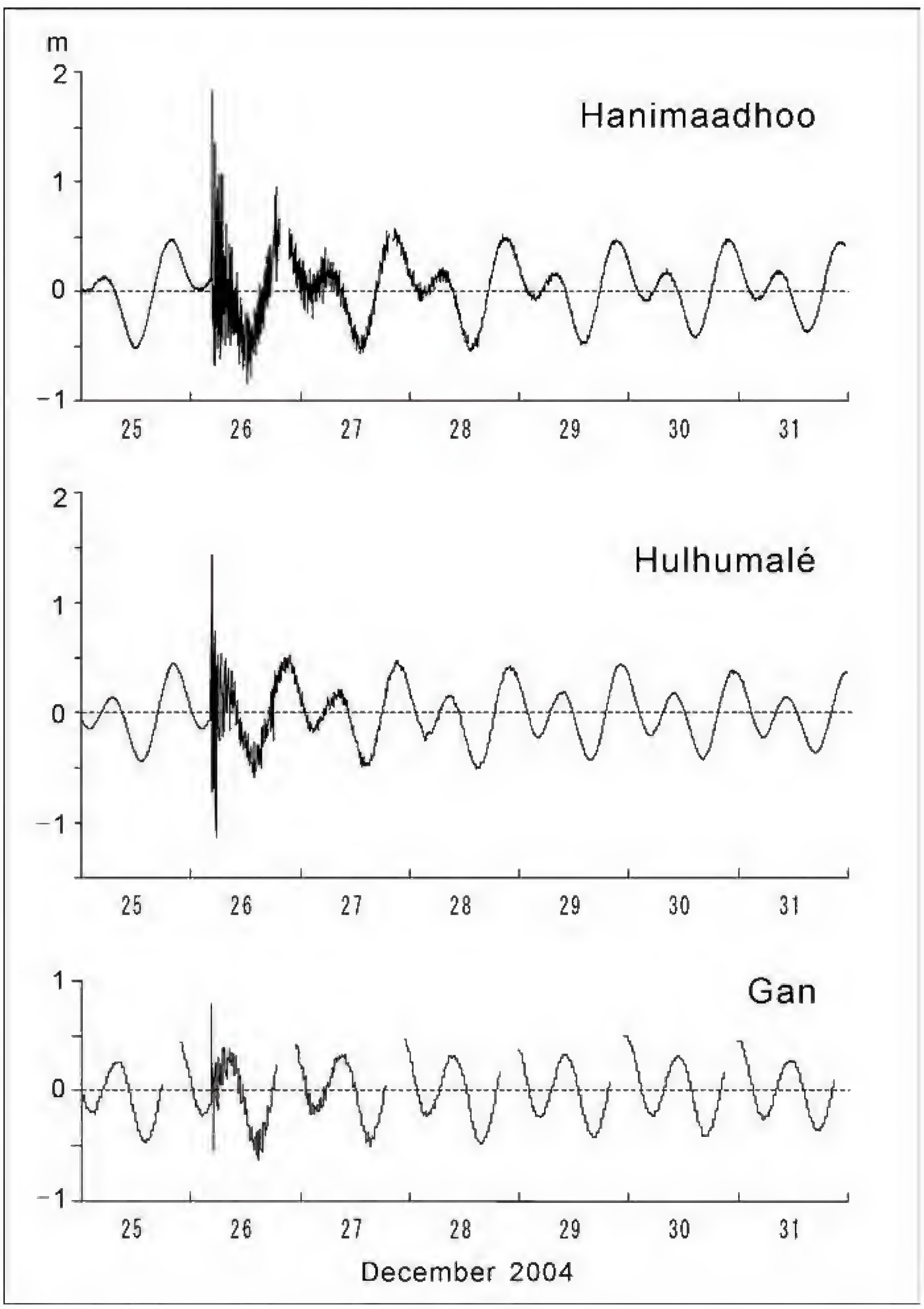

Figure 2. Tide gauge observations for December 2004 Indian Ocean Tsunami in the Maldives (University of Hawaii, Sea Level Center: http://uhslc.soest.hawaii.edu).

At Hanimaadhoo, the lower peak (60.4 to 66.5 cm below MSL) appeared 20 to 32 minutes and the second highest peak (135.3 cm above MSL) 42 minutes after the primary highest peak. At Hulhumalé, the lower peak (67.7 cm below MSL) appeared 16 minutes and the second highest peak (74.0 cm above MSL) 36 minutes after the primary highest peak. At Gan, the lower peak (51.6 to 54.0 cm below MSL) appeared 16 to 28 minutes and the second highest peak (25.5 cm above MSL) 40 minutes after the primary highest peak (Fig. 2).

Disaster Status

Following the tsunami, there were 82 confirmed deaths, 26 people missing and more than 3,997 reports of house/building damage (Maldive Government, January 12, 2005). Ten days after the tsunami, on January 5, 2005, records show there remained 12,478 refugees. The disaster status for inhabited islands is summarized in Table 1, where data of the number of deaths, missing persons, displaced population, damaged buildings, flooded area versus land area, vessel damage, status of electric supply, telephone availability, and water and food supplies were released by the Maldive Government at 21:00 on January 5, 2005. The tsunami arrival time was surveyed by telephone for each island office by the Environment Research Centre, Maldive Government. These arrival times may involve some reporting errors, and data could not be collected from islands in the southern atolls due to a break in telephone service after the tsunami. For Hanimaadhoo, Hulhumalé and Gan the maximum tide recorded by the tide gauges was recorded as the tsunami arrival time. Figure 3 shows the distribution of dead and missing persons according to location on inhabited islands.

The greatest disaster occurred in the southern Maldives, with 88 of the 108 reported deaths/missing persons occurring south of South Malé Atoll in Kaafu. Four deaths were reported north of North Malé Atoll. These disaster status data do not necessarily correspond with the tide gauge data which indicates greater tsunami height in the northern atoll. In the southern Maldives, the eastern islands suffered greatly, while in the northern Maldives, the disaster also affected the western islands and lagoon islands. Such data may reflect a difference in the effects of the tsunami on the northern and southern atolls.

SURVEY SITE AND METHODS

We investigated 43 islands (35 inhabited, 8 uninhabited) in the northern to the southern Maldives during February-to-March and August 2005. We selected many islands at the eastern atoll rim where the tsunami initially surged and included islands without damage in the northern Maldives.

We measured profiles across islands to observe topographic features. On the inhabited islands, the profile transect was set across villages where there were many traces of tsunami in buildings. The measured watermarks and land use around transects were projected on the profiles. These watermarks were measured by confirming other watermarks at a similar height around the measured points together with other

Table 1. Tsunami disaster in the Maldives

ATOLL Map index No.	Island	Area[1] (ha) May 2003	Population in mid 2004 [2]	Tsunami arrival time[3]	Death	Missing	Displaced population	Damaged buildings	Flooded area vs. land area	Vessels lost	Vessels damaged	Electricity	Telephone	Water	Food
					Disaster Status at January 5, 2005 [2]							(A: available, N/A: not available, N: needed, A(N): available and needed, —: not stated)			
HAA ALIFU (North Thiladhunmathee Atoll)															
HA01	Thuraakunu	22.0	373		0	0	0	0	1/4			A	—	A	A
HA02	Uligamu	112.7	276		0	0	0	0	—			A	—	A	A
HA03	Berinmadhoo	14.6	92	9:30	0	0	0	0	—			A	—	A	A
HA04	Mulhadhoo	118.2	202	9:15	0	0	0	0	<1/4			A	—	—	A
HA05	Hathifushi	4.1	121	9:40	0	0	0	0	<1/4			A	—	A	A
HA06	Hoarafushi	63.1	2,252	9:40	0	0	0	0	1/2			A	N/A	A	A
HA07	Ihavandhoo	60.5	2,395	9:15	0	0	0	0	1/3			A	—	—	A
HA08	Maarandhoo	41.1	444	9:35	0	0	0	0	<1/4			A	—	A	A
HA09	Thakandhoo	45.0	408	9:55	0	0	0	0	<1/4			A	—	N/A	A
HA10	Dhidhdhoo	50.6	2,735	9:30	0	0	0	0	<1/4			A	—	—	A
HA11	Vashafaru	31.4	417	9:03	0	0	0	70	1/2		1	A	—	A	A
HA12	Kelaa	213.4	1,370	9:40	0	0	0	0	<1/4			A	—	A	A
HA13	Filladhoo	225.6	581	9:45	0	0	669	97	1			A	N/A	N/A	N/A
HA14	Baarah	248.8	1,153	9:30	0	0	0	4	1			A	—	A(N)	A
HA15	Muraidhoo	49.5	404	9:55	0	0	0	4	<1/4			A	—	—	A
HA16	Utheemu	47.0	510	9:40	0	0	0	5	1/4			A	—	A	A
HAA DHAALU (South Thiladhunmathee Atoll)															
HD01	Hanimaadhoo	259.5	1,099	9:30 (9:40*)	0	0	0	0	<1/4			A	N/A	A	A
HD02	Nolhivaranfaru	150.2	280	9:20	0	0	0	2	1/3		1	A	A	A	A
HD03	Nolhivaramu	221.1	1,526	9:40	0	0	0	0	<1/4			A	A	A	A
HD04	Kulhudhuffushi	172.2	7,930	9:23	0	0	0	36	<1/4			A	A	A	A
HD05	Kumundhoo	178.4	853	9:30	0	0	0	0	1/3			A	A	A	A
HD06	Maavaidhoo	36.5	366	9:35	0	0	0	0	1/4			A	A	A	A
HD07	Faridhoo	23.3	114	9:45	0	0	0	0	1/4			A	N/A	A	A
HD08	Finey	118.4	266	9:30	0	0	0	0	<1/4			A	A	A	A
HD09	Hirimaradhoo	42.9	276	9:30	0	0	0	0	1/4			A	—	A	A
HD10	Kuribi	31.6	405	9:00	0	0	0	0	<1/4			A	N/A	A	A
HD11	Kuburudhoo	41.8	142	9:40	0	0	0	0	<1/4			A	N/A	A	A
HD12	Vaikaradhoo	96.5	1,080	9:45	0	0	0	0	1/4			A	A	A	A
HD13	Neykurendhoo	163.0	758	9:25	0	0	0	0	<1/4			A	A	A	A
HD14	Naivaadhoo	25.7	383	9:15	0	1	0	0	1/3			A	—	A(N)	A
HD15	Nellaidhoo	29.7	632	9:45	0	0	0	0	1/2			A	A	N/A	A
HD16	Makunudhoo	60.7	1,031	9:00?	0	0	0	0	—			A	—	A	A
SHAVIYANI (North Miladhunmadulu Atoll)															
S01	Noomaraa	35.4	408		0	0	0	0	—			A	N/A	A	A
S02	Feevah	79.2	754		0	0	0	0	1/2			A	A	A	A
S03	Milandhoo	125.5	1,198		0	0	0	0	1/3			A	—	A	A
S04	Maakandoodhoo	90.7	399		0	0	0	0	1/3			A	N/A	A	A
S05	Funadhoo	86.4	1,369		0	0	0	0	1/2			A	—	A	A
S06	Maaugoodhoo	26.7	740		0	0	0	2	<1/4			A	A	N/A	A
S07	Feydhoo	81.7	698		0	0	0	0	1/3		1	A	A	A	A
S08	Foakaidhoo	55.6	1,352		0	0	0	0	<1/4		3	A	A	A	A
S09	Narudhoo	41.8	378		0	0	0	6	1/4			A	—	A	A
S10	Lhaimagu	37.4	644		0	0	0	0	—			A	A	A	A
S11	Kaditheemu	89.8	1,093		0	0	0	0	<1/4			A	A	A	A
S12	Goidhoo	106.2	378		0	0	0	0	1/3			A	N/A	A	A
S13	Bilehffahi	58.4	383		0	0	0	0	1/3			A	A	A	A
S14	Maroshi	26.7	557		0	0	0	0	1/3			A	N/A	N	A
S15	Komandhoo	6.0	1,456		1	0	0	0	—		22	A	—	A	N/A
NOONU (South Miladhunmadulu Atoll)															
N01	Hebadhoo	19.7	389	9:15	0	0	0	0	<1/4			A	A	A	A
N02	Kedhikolhudhoo	218.7	1,185	9:20	0	0	0	0	1/2	1	3	—	A	A	A
N03	Maalhendhoo	33.6	466	9:00	0	0	0	1	<1/4			—	—	A	A
N04	Landhoo	81.2	578	9:00	0	0	0	0	<1/4			Partially	A	A	A
N05	Maafaru	114.3	664	9:25	0	0	0	110	1	2		N/A	A	A(N)	N/A
N06	Manadhoo	92.2	1,204	9:30	0	0	0	0	1/4		1	—	—	A	A
N07	Kudafari	22.5	401	9:15	0	0	0	12	1			N/A	A	A	A
N08	Lhohi	35.2	513	9:00	0	0	0	0	1/2			—	A	A	A
N09	Miladhoo	18.1	827	9:15	0	0	0	0	1/4			—	—	A	A
N10	Magoodhoo	30.5	208	9:15	0	0	0	0	<1/4			—	—	A	A
N11	Holhudhoo	17.2	1,589	9:15	0	0	0	15	1/2		4	—	A	A	A
N12	Fodhdhoo	24.6	187	9:20	0	0	0	0	<1/4			—	A	A	A
N13	Velidhoo	42.6	1,833	9:30	0	0	0	0	<1/4			—	—	A	A
RAA (North Maalhosmadulu Atoll)															
R01	Alifushi	45.6	1,751		0	0	0	0	—			A	—	A	A
R02	Vaadhoo	31.3	321	9:15	0	0	0	30	1/2			A	N/A	A	A
R03	Rasgetheemu	30.4	500	9:30	0	0	0	0	—			A	—	N	A
R04	Agolhitheemu	31.7	267	9:30	0	0	0	0	—			A	N/A	A	A
R05	Hulhudhuffaaru	48.6	1,017	9:30	0	0	0	0	<1/4			A	A	A(N)	A
R06	Ugoofaaru	28.1	1,271	9:30	0	0	0	0	<1/4			A	—	A	A
R07	Maakurathu	43.4	837	9:30	0	0	0	0	<1/4			A	A	A	A
R08	Rasmaadhoo	22.7	488	9:37	0	0	0	0	1/3			A	—	A	A
R09	Innamaadhoo	27.8	528	9:40	0	0	0	0	1/4			A	A	A	A
R10	Iguraidhoo	35.8	1,373	9:30	0	0	0	0	1/3			A	A	A	A
R11	Fainu	50.1	276	9:20	0	0	0	46	1/2			A	N/A	A	N/A
R12	Kinolhas	44.9	399	9:15	0	0	0	0	1/4			A	A	A	A
R13	Meedhoo	30.6	1,595	9:15	0	0	0	0	<1/4			A	A	A	A
R14	Maduvvari	16.4	1,551	9:45	0	0	0	258	1/2			A	A	A	A
R15	Kandholhudhoo	11.2	3,157		3	0	3,144	520	1		5	A	A	N/A	N/A

ATOLL / Map index No.	Island	Area[1)] (ha) May 2003	Population in mid 2004 [2)]	Tsunami arrival time[3)]	Disaster Status at January 5, 2005 [2)] Death	Missing	Displaced population	Damaged buildings	Flooded area vs. land area	Vessels lost	Vessels dam-aged	Electricity	Telephone	Water	Food (A: available, N/A: not available, N: needed, A(N): available and needed, —: not stated)
BAA (South Maalhosmadulu Atoll)															
B01	Kudarikilu	13.7	317		0	0	0	0	<1/4			A	A	A	A
B02	Kamadhoo	16.2	426		0	0	0	4	1/2			A	A	A	A
B03	Daravandhoo	45.5	746		0	0	0	0	1			A	A	A	A
B04	Maalhos	23.2	318		0	0	0	0	1			A	—	A	A
B05	Eydhafushi	22.2	2,476		0	0	0	25	1		5	A	A	A(N)	A
B06	Kendhoo	14.5	863		0	0	0	3	1			A	A	A(N)	A
B07	Kihaadhoo	26.4	267		0	0	0	2	1			A	N/A	A(N)	A
B08	Dhonfanu	12.6	304		0	0	0	0	1			A	—	A	N/A
B09	Hithaadhoo	28.4	895		0	0	0	0	1/3			A	N/A	A	A
B10	Thulhaadhoo	5.0	1,921		0	0	0	0	<1/4			A	—	A	A
B11	Goidhoo	113.5	469		0	0	0	0	1/2			A	A	A	A
B12	Fehendhoo	20.6	131		0	0	0	0	1/3		1	A	A	A	A
B13	Fulhadhoo	31.5	211		0	0	0	35	1/4		2	A	A	A	A
LHAVIYANI (Faadhippolhu Atoll)															
L01	Hinnavaru	12.6	2,900		0	0	0	1	1		5	A	—	A(N)	A
L02	Naifaru	14.3	3,667		0	0	0	0	1/3			A	—	A	N/A
L03	Maafilaafushi	49.2	147		0	0	0	24	1/2		3	A	A	A	A
L04	Kurendhoo	19.7	1,096		0	0	0	0	<1/4			A	—	A	A
L05	Olhuvelifushi	19.9	348		0	0	0	0	<1/4			A	N/A	—	A
KAAFU (Malé Atoll)															
K01	Kaashidhoo	276.5	1,764	9:15	0	0	0	9	1			A	—	N	N/A
K02	Gaafaru	10.0	758	9:15	0	0	0	125	1			A	—	A	A
K03	Dhiffushi	18.8	862	9:15	0	0	556	0	1		4	A	—	A	A
K04	Thulusdhoo	33.5	857	9:00	0	0	0	42	1/3			A	A	A	A
K05	Huraa	18.8	709	9:20	0	0	0	5	1			A	A	N/A	N/A
K06	Himmafushi	24.8	762	9:20	0	0	0	60	—			A	—	A	A
K07	Gulhi	5.5	601	9:15	1	0	0	9	1/2		1	A	—	A	A
K08	Maafushi	23.3	976	9:25	0	0	0	162	1			A	N/A	N/A	—
K09	Guraidhoo	18.2	1,169	9:15	2	2	1,132	70	1			A	A	A	—
CAPITAL															
	Malé	197	74,069#	9:24*	0	0	0	0	1/2			A	A	A	A
ALIFU ALIFU (North Ari Atoll)															
AA01	Thoddoo	142.2	1,114		0	0	0	0	—			A	—	A	A
AA02	Rasdhoo	16.5	992		0	0	0	0	1/2	2		A	—	A	A
AA03	Ukulhas	17.4	507		0	0	0	84	1			A	A	A	A
AA04	Bodufolhudhoo	6.9	472		0	0	0	0	1		5	A	—	A	A
AA05	Mathiveri	20.2	465		0	0	20	77	1		3	A	—	A(N)	A
AA06	Feridhoo	43.2	551		0	0	0	0	1/3		1	A	—	A	A
AA07	Maalhos	23.2	352		0	0	0	0	1/3			A	—	A	A
AA08	Himendhoo	16.4	542		0	0	0	3	1/2			A	—	A	A
ALIFU DHAALU (South Ari Atoll)															
AD01	Hangnameedhoo	17.3	44		0	0	0	0	1/3			A	A	A	A
AD02	Omadhoo	21.1	701		0	0	0	1	<1/4			A	—	A	A
AD03	Kuburudhoo	4.9	352		0	0	0	4	1/4			A	—	A	A
AD04	Mahibadhoo	17.7	1,825		0	0	0	1	1/3		8	A	—	A	A
AD05	Dhagethi	21.4	757		0	0	0	12	1	1	4	A	—	A	A
AD06	Dhigurah	42.8	351		0	0	0	7	1			A	—	A	A
AD07	Dhidhdhoo	13.4	85		0	0	0	5	1			A	—	A	A
AD08	Maamigili	74.9	1,657		0	0	0	0	—			A	—	—	A
AD09	Fenfushi	16.5	585		0	0	0	0	1/3			A	A	A	A
AD10	Mandhoo	28.8	286		0	0	0	0	1			A	—	—	A
AD-R1	Ari Beach Resort				1	0									
VAAVU (Felidhe Atoll)															
V01	Fulidhoo	9.7	340		0	0	0	16	1			A	—	A	A
V02	Thinadhoo	9.1	63		1	0	0	31	1			A	—	A	A
V03	Felidhoo	11.8	457		0	0	0	64	1			A	—	A	A
V04	Keyodhoo	7.3	570		0	0	450	83	1		2	A	—	A	A
V05	Rakeedhoo	4.0	150		0	0	47	16	1			A	A	A	A
MEEMU (Mulaku Atoll)															
M01	Dhiggaru	7.3	926		1	0	0	0	1			A	—	—	A
M02	Maduvvari	3.7	375		0	6	0	0	1			A	—	—	N/A
M03	Raiymandhoo	21.6	174		0	0	0	20	1			A	A	A	A
M04	Madifushi	10.9	99		2	0	90	20	1			N/A	—	A(N)	N/A
M05	Veyvah	34.5	154		0	0	12	25	1			A	—	—	A
M06	Mulah	57.8	1,198		1	0	0	0	—			A	—	A	A
M07	Muli	28.9	750		5	1	650	135	1			A	—	A(N)	N/A
M08	Naalaafushi	8.9	291		1	0	460	0	1		2	A	—	N/A	N/A
M09	Kolhufushi	75.6	878		10	6	1,000?	146	1	1	1	A	A	N	N/A
M-R1	Hakuraa Club Resort				1	0									
FAAFU (North Nilandhe Atoll)															
F01	Feeali	13.6	876		0	0	0	2	1			A	—	A	A
F02	Biledhdhoo	29.5	1,024		0	0	0	0	1/4			A	—	A	A
F03	Magoodhoo	17.7	460		0	0	0	0	1	18		A	A	A	A
F04	Dharaboodhoo	36.5	236		0	0	0	0	—			A	A	A	A
F05	Nilandhoo	49.0	1,268		0	0	0	0	1/2		2	A	—	A	A
DHAALU (South Nilandhe Atoll)															
D01	Meedhoo	8.9	899		0	0	0	0	1			A	N/A	A(N)	N/A
D02	Badidhoo	19.9	718		0	0	0	0	<1/4		5	A	—	A	A

ATOLL Map index No.	Island	Area[1] (ha) May 2003	Population in mid 2004 [2]	Tsunami arrival time[3]	Disaster Status at January 5, 2005 [2] Death	Missing	Displaced population	Damaged buildings	Flooded area vs. land area	Vessels lost	Vessels dam-aged	Electricity	Telephone	Water	Food
												(A: available, N/A: not available, N: needed, A(N): available and needed, —: not stated)			
D03	Gemendhoo	4.7	290		5	3	340	76	1			N/A	—	A	A
D04	Vaanee	10.9	240		0	1	281	40	1			N/A	—	A	N/A
D05	Maaeboodhoo	17.6	571		0	0	0	0	1			A	—	A	A
D06	Ribudhoo	16.1	341		2	0	112	56	1		10	A	N/A	—	N/A
D07	Hulhudheli	15.5	555		0	0	9	0	1			A	—	A	A
D08	Kudahuvadhoo	67.0	1,326		0	0	0	0	1/2			A	—	A	A
D-R1	Velavaru Resort				2	0									
THAA (Kolhumadulu Atoll)															
T01	Buruni	30.5	210		0	0	0	0	1/2			A	A	A(N)	A
T02	Vilufushi	13.5	1,156		14	4**	813	192	1			A	N/A	N	N/A
T03	Madifushi	17.7	667		1	0	26	111	1			N/A	N/A	N	A
T04	Dhiyamigili	23.5	442		0	0	0	0	1			A	—	A(N)	A
T05	Guraidhoo	26.9	1,161		0	0	0	46	1			A	—	A(N)	A
T06	Gaadhiffushi	11.0	219		0	0	0	0	1			N/A	A	A	A
T07	Thimarafushi	14.5	1,289		0	0	0	214	1			A	A	A(N)	—
T08	Veymandhoo	40.8	804		0	0	0	0	1			A	—	A	A
T09	Kibidhoo	30.8	796		0	0	0	0	1			A	A	A(N)	A
T10	Omadhoo	32.8	386		0	0	0	0	1			A	A	A	A
T11	Kadoodhoo	78.2	329		0	0	0	0	1			A	—	A	A
T12	Vandhoo	23.2	254		0	0	0	0	1			A	A	A	A
T13	Hirilandhoo	25.1	800		0	0	0	0	1			A	A	A	A
LAAMU (Hadhdhunmathee Atoll)															
L01	Isdhoo	293.7	1,372		6	0	0	0	1			A	—	N/A	N/A
L02	Dhabidhoo	46.6	464		2	0	464	77	1			A	—	A	N/A
L03	Maabaidhoo	43.3	764		2	1	0	0[?]	1			A	—	—	A
L04	Mundhoo	19.7	504		6	1	—	84	1		7	A	—	—	N/A
L05	Kalhaidhoo	24.8	456		2	1	—	76	1			A	—	—	N/A
L06	Gan	516.6	2,150		0	0	—	48	1/2	1		A	—	N/A	A
L07	Kaddhoo (Airport)		0		0	0	0	0	1			A		—	
L08	Fonadhoo	159.2	1,760		4	0	0	0	1/2			A	—	—	A
L09	Gaadhoo	69.4	231		0	0	0	0	1			A	N/A	A	A
L10	Maamendhoo	18.8	907		0	0	0	0	<1/4			A	—	N/A	A
L11	Hithadhoo	108.7	749		0	0	0	0	<1/4			A	—	—	A
L12	Kunahandhoo	81.3	514		0	0	0	0	1			A	—	A	A
L13	Maavah	31.8	1,447		0	0	0	0	<1/4			A	—	—	A
GAAFU ALIFU (North Huvadhoo Atoll)															
GA01	Viligili	55.0	2,193		1	0	1,936	0	1/3			A	—	A(N)	A
GA02	Maamendhoo	48.5	1,048		0	0	0	174	1			A	A	A	—
GA03	Nilandhoo	56.7	427		0	0	—	5	1/2			A	A	A	A
GA04	Dhaandhoo	12.6	1,178		1	0	253	50	1			A	A	N	A
GA05	Kodey	104.4	287		0	0	0	0	1/2			A	N/A	A	A
GA06	Dhiyadhoo	48.8	92		0	0	0	15	1			A	A	A	—
GA07	Gemanafushi	47.2	947		0	0	0	157	1/2			A	N/A	A	—
GA08	Kanduhulhudhoo	25.2	451		0	0	0	0	1/2		4	A	—	A	A
GA09	Dhevvadhoo	20.5	446		0	0	0	0	—			A	—	A	A
GA10	Kolamaafushi	20.3	1,118		0	0	0	0	1			A	A	A	A
GAAFU DHAALU (South Huvadhoo Atoll)															
GD01	Thinadhoo	104.4	3,834		0	0	0	0	<1/4			A	—	A	A
GD02	Madaveli	33.8	5		0	0	0	0	—			A	—	A	A
GD03	Hoadedhdhoo	88.1	575		0	0	0	0	<1/4			A	—	A	A
GD04	Nadallaa	41.4	635		0	0	0	0	<1/4			A	—	A	A
GD05	Rathafandhoo	35.2	461		0	0	0	0	1/2			A	—	A	A
GD06	Fiyoari	72.6	736		0	0	0	0	<1/4			A	—	—	A
GD07	Maathodaa	15.6	485		0	0	0	0	<1/4			A	—	A	A
GD08	Fares	21.6	443		0	0	0	0	<1/4			A	—	A	A
GD09	Vaadhoo	167.3	727		2	0	0	0	1/2			A	—	A	A
GD10	Gadhdhoo	22.2	1,543		0	0	0	0	1/3		3	A	N/A	A	A
GNAVIYANI (Foammulah Atoll)															
G01	Foammulah	420.0	7,645		1	0	0	0	<1/4			A	—	A	—
SEENU (Addu Atoll)															
S01	Meedhoo	49.2	1,541		0	0	0	0	1/4			A	—	A	A
S02	Hulhudhoo	31.4	1,144		0	0	14	30	1/3			A	—	A	A
S03	Hithadhoo	467.3	9,277		0	0	0	0	1/2		2	A	—	A	A
S04	Maradhoo	151.8	2,049		0	0	0	0	1/2			A	—	A	A
S05	Maradhoo-Feydhoo	74.9	1,086		0	0	0	0	<1/4			A	N/A	A	A
S06	Feydhoo	166.0	2,883		0	0	0	0	<1/4			A	—	A	A
S07	Gan			9:54*											
total		11,638	258,039[##]		81	27	12,478	3,397		26	121				

[#] Population on March 31, 2000 [1]
[##] Population of the Republic of Maldives on March 31, 2000 is 270,101 [1], and on March 28, 2006 is 298,842 [4].
*Tide gauge data collected by the Univeristy of Hawaii's Sea Level Center *(http://uhslc.soest.hawaii.edu)*
** Original number was 3; 1 added by authors based on updated information
[?] Uncertainty marked by the authors

1) Maldive Government (2004) Statistical Yearbook of Maldives 2004 *(http://www.planning.gov.mv)*
2) Maldive Government (2005) Assessment of damage (inhabited islands) data for 200 islands, *(http://www.presidencymaldives.gov.mv)*
3) Data collected by the Environment Research Centre, Maldive Gorvenment
4) Maldive Govrenment (2006) Statistical Yearbook of Maldives 2006 *(http://www.planning.gov.mv/publications/yrb2006)*

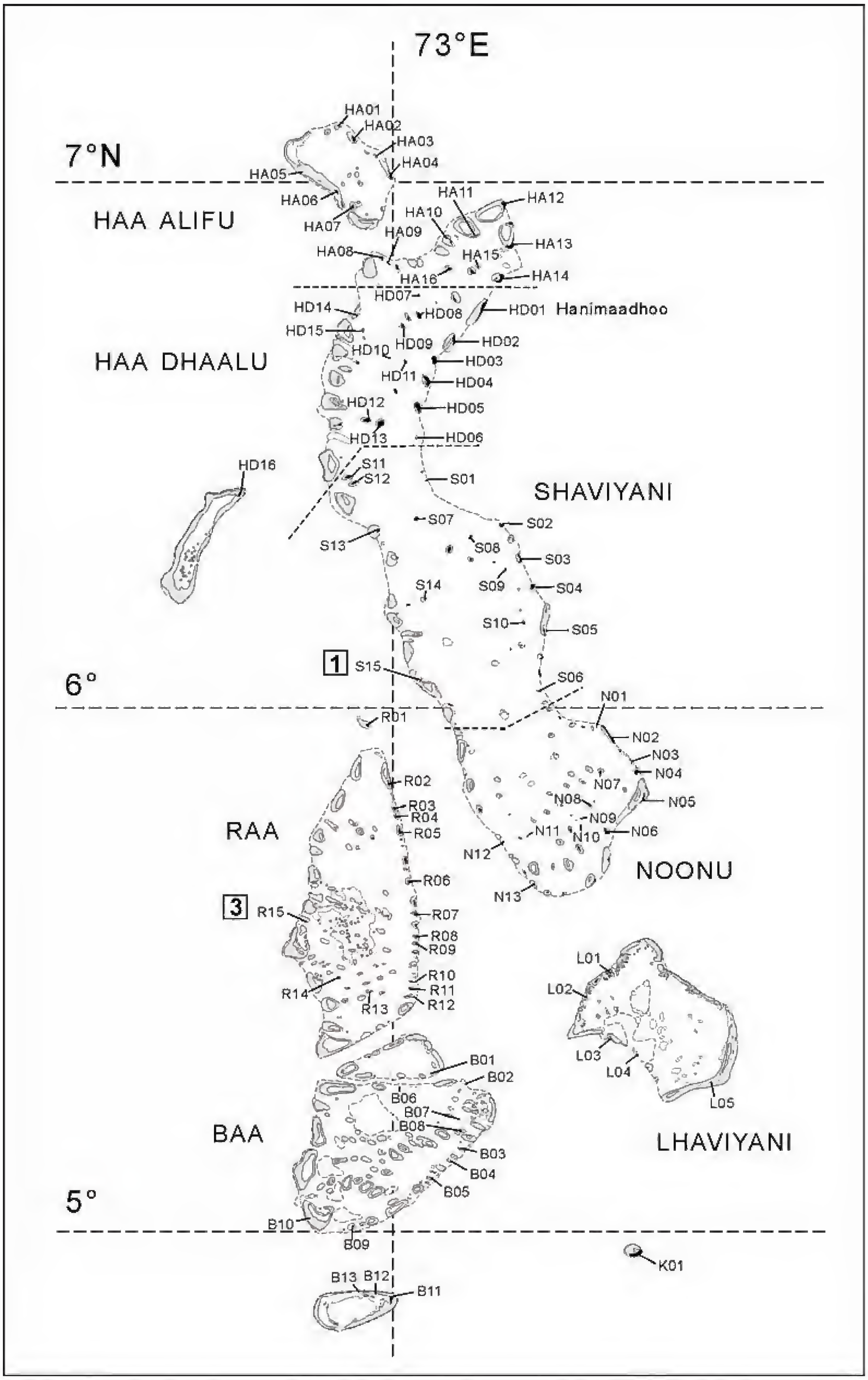

Figure 3-1. Location of islands in the northern atolls of the Maldives and distribution of deaths due to the 2004 tsunami (numbers in squares).

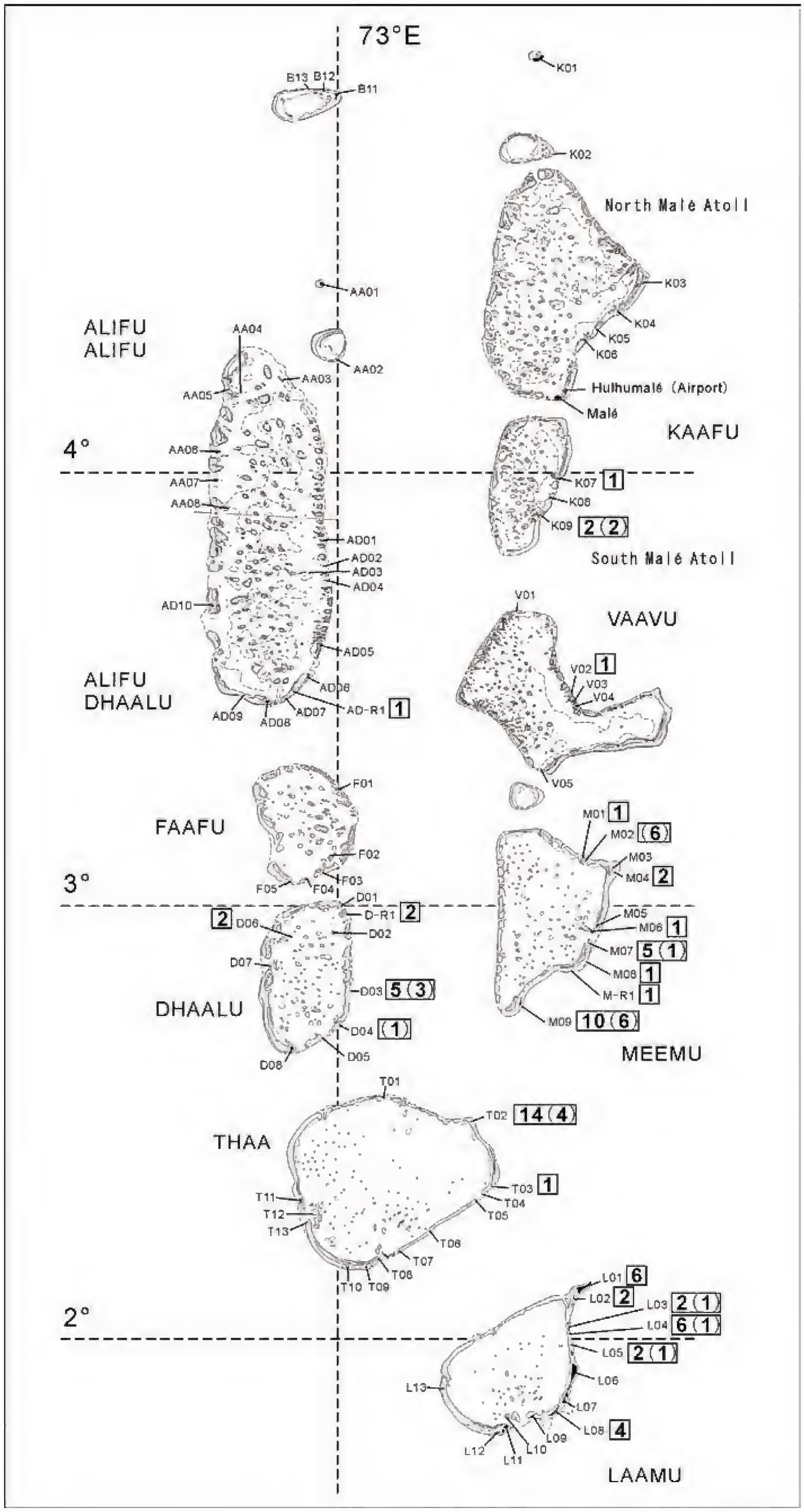

Figure 3-2. Location of islands in the middle and southern atolls of the Maldives and distribution of deaths and missing (in parentheses) due to the 2004 tsunami (numbers in squares).

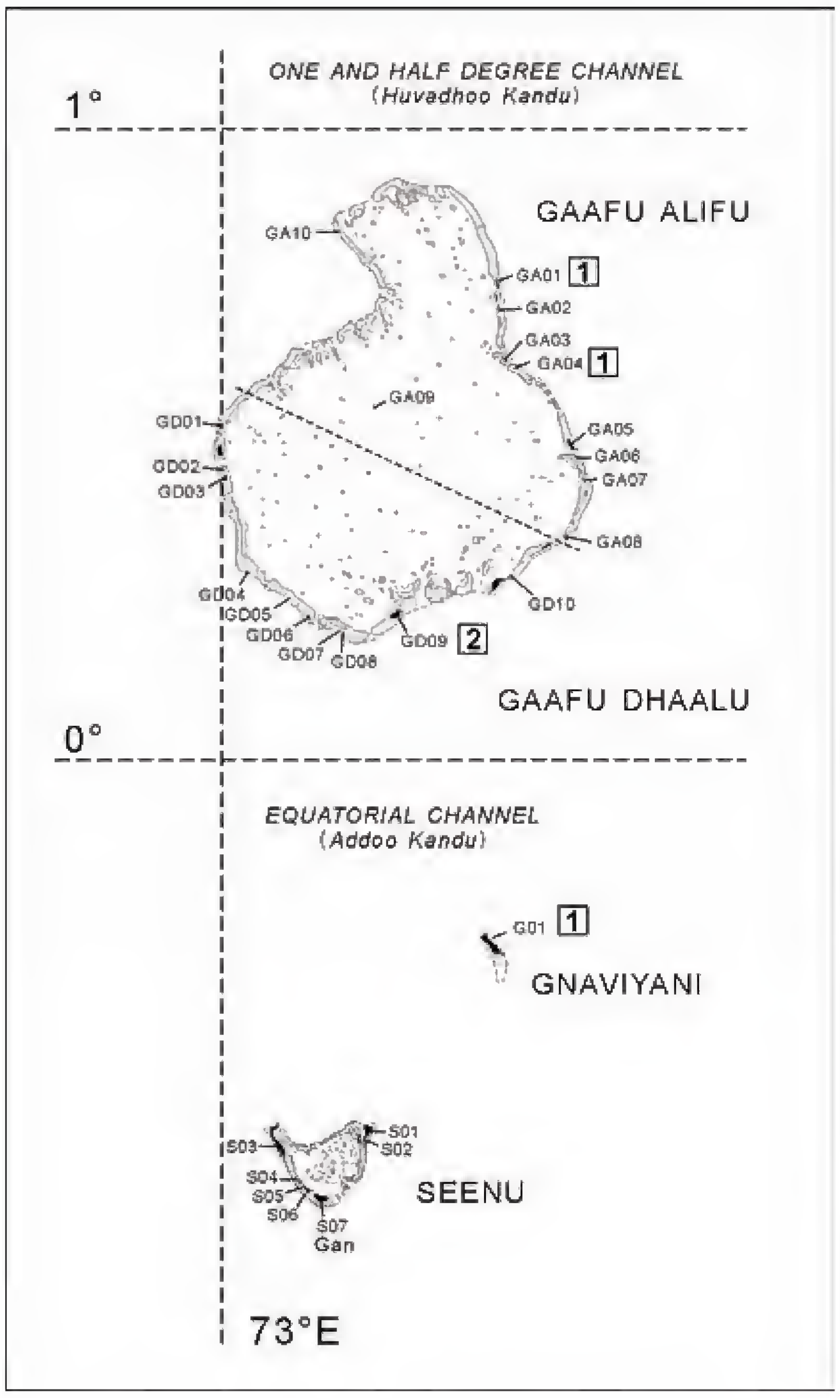

Figure 3-3. Location of islands in the far-south atolls of the Maldives and distribution of deaths due to the 2004 tsunami (numbers in squares).

evidence such as eyewitness accounts in order to build an understanding of the tsunami movements over a wide area. We interviewed local residents to determine wave direction, number, interval, height, and relation to watermarks, and also gathered information concerning the evacuation procedures of the local population in disaster areas in the southern atolls.

A semi-automatic (optical) level is used for survey. Height data are based on the apparent sea levels with tide-level corrections. Mean sea levels at Hanimaadhoo (209.6 cm), Hulhumalé (187.8 cm), Gan (154.9 cm) were calculated by the University of Hawaii's Sea Level Center based on observations from October 1992 to October 1993 for Hanimaadhoo, June 1992-to-June 1993 for Hululemalé, and January to December 1992 for Gan. The highest and lowest tide levels are based on the hourly observed extreme tide level data recorded by the Sea Level Center between 1991-to-2002 (12 years) for Hanimaadhoo, 1989-to-2001 (13 years) for Hulhumalé, and 1987-to-2001 (15 years) for Gan, although the hourly tide dataset has some missing data at each site. The highest and lowest tide levels are 283 cm (73.4 cm above MSL) and 129 cm (80.6 cm below MSL) at Hanimaadhoo, 255.7 cm (67.9 cm above MSL) and 111.3 cm (76.5 cm below MSL) at Hulhumalé, 236.0 cm (81.1 cm above MSL) and 78.0 cm (76.9 cm below MSL) at Gan, respectively.

The tide data at Hanimaadhoo are adopted for Haa Alifu, Haa Dhaalu and Raa Atolls in the northern Maldives. The tide data at Hulhumalé are used as the reference tide for Kaafu Atoll (North and South Malé Atolls). We observed tidal change at Fonadhoo in Laamu Atoll between 8:00 on August 26 and 1:00 on August 27, 2005 in order to evaluate the reference tide for the atolls between Kaafu and Seenu. The observed tidal change agrees with the tidal change at Gan rather than at Hulhumalé (Fig. 4). Therefore, we adopted the tide data at Gan for Laamu Atoll. For the atolls between Laamu and Kaafu, the tide data at Gan are adopted for Thaa, and the tide data at Hulhumalé are adopted for Vaavu, Meemu, Faafu and Dhaalu Atolls by taking the distance between Fonadhoo and Hulhumalé into consideration.

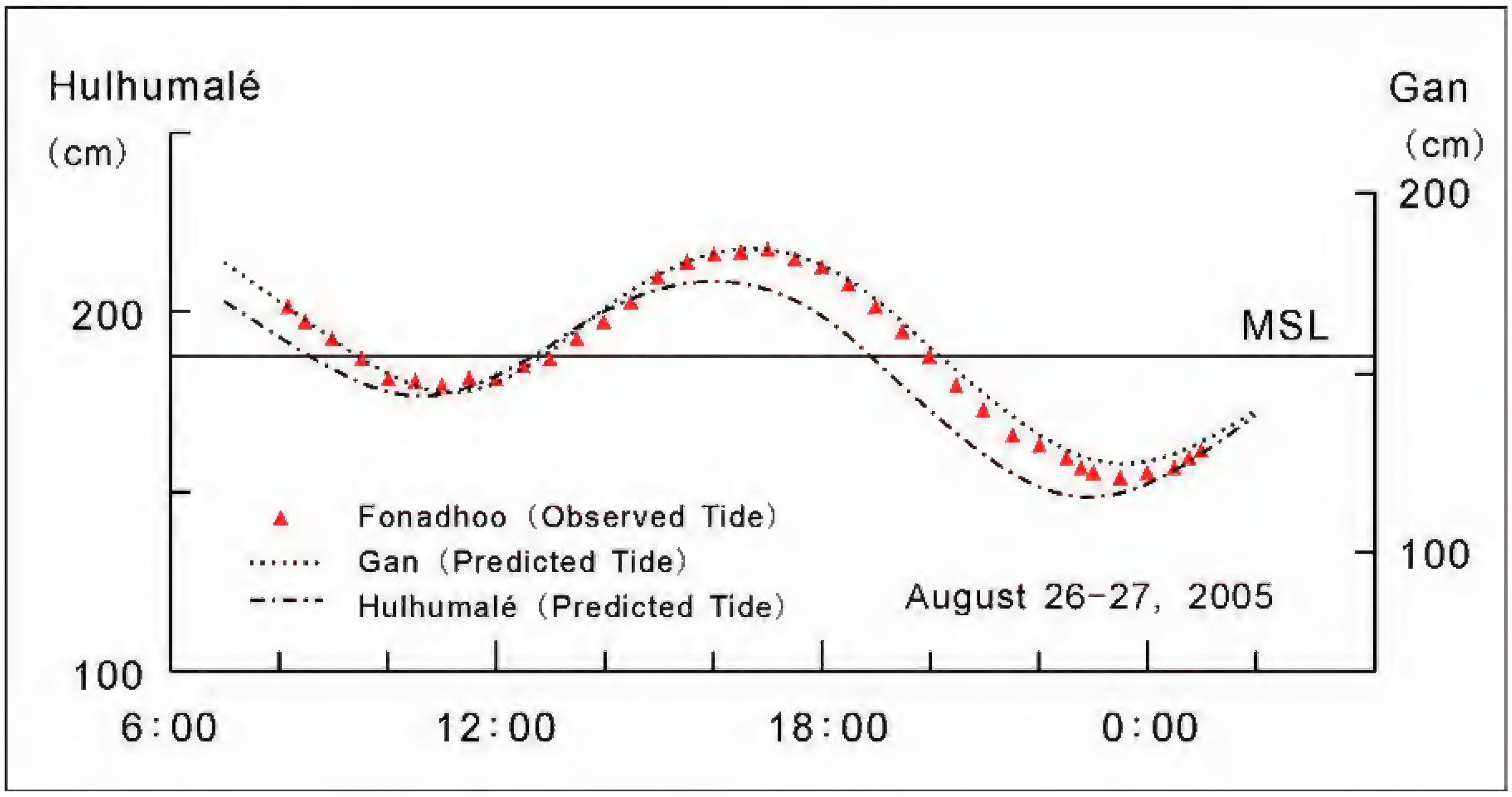

Figure 4. Sea level observation for leveling at Fonadhoo, Laamu Atoll (8:00 August 26 to 1:00 August 27, 2005) and tide gauge data at Hulhumalé and Gan.

TSUNAMI DISASTER AND ISLAND TOPOGRAPHY IN THE NORTHERN MALDIVES

Haa Alifu and Haa Dhaalu

Haa Alifu (North Thiladhunmathee Atoll) and Haa Dhaalu (South Thiladhunmathee Atoll) constitute the northern region (6°12' to 7°07' N, 72°33' to 73°14' E) of a large atoll extending about 150 km in a N-S direction and about 30-to-40 km in an E-W direction in the northern Maldives. The atoll rim consists of many faroes and Indian Ocean swells enter the atoll lagoon. Large islands developed in this area, some of which have fresh water/ brackish water lakes with mangroves. In this area, we surveyed nine inhabited islands with and without tsunami damage (Fig. 5).

Maarandhoo. A NW-SE (300˚-120˚) profile was measured on Maarandhoo located at the northwestern rim of the atoll (Fig. 6). A sand dune, as high as 4 m above MSL, developed in the northwestern part of the island, and there is a settlement located on the southeastern side at a height of 2 m above MSL (Fig. 7). No tsunami damage occurred.

Vashafaru. Vashafaru is located at the southern end (lagoon-side) of a faro in the northeastern Haa Alifu Atoll. A profile across the island was measured along a road to the jetty (Fig. 8). The maximum width of the island is about 250 m, which is smaller than for other islands in this atoll.

A beach ridge at a height of 2.1 m above MSL formed in the northern side of the island. A line of scarping was observed along the northern beach (Photo 1). The local residents report that the height of tsunami from the northern faro lagoon was higher than the jetty of 1.6 m above MSL. No damage was reported for the wave from this direction.

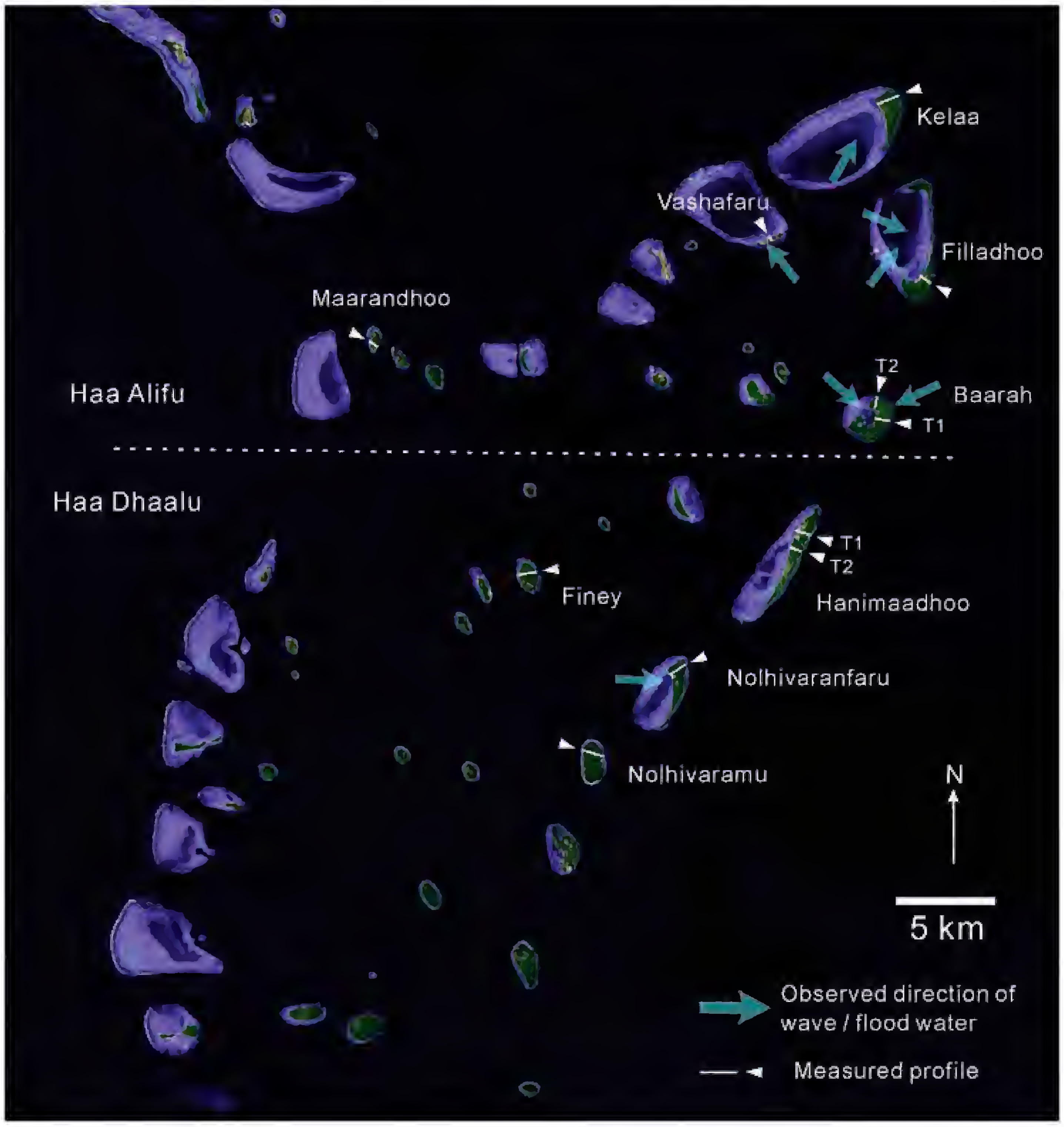

Figure 5. Research area in the northern Maldives (Haa Alifu, Haa Dhaalu) and flood water direction observed by inhabitants. The satellite image (January 1, 1999) is provided by Digital Globe.

Figure 6. Location of transect on Maarandhoo, Haa Alifu. The satellite image is provided by Google Earth.

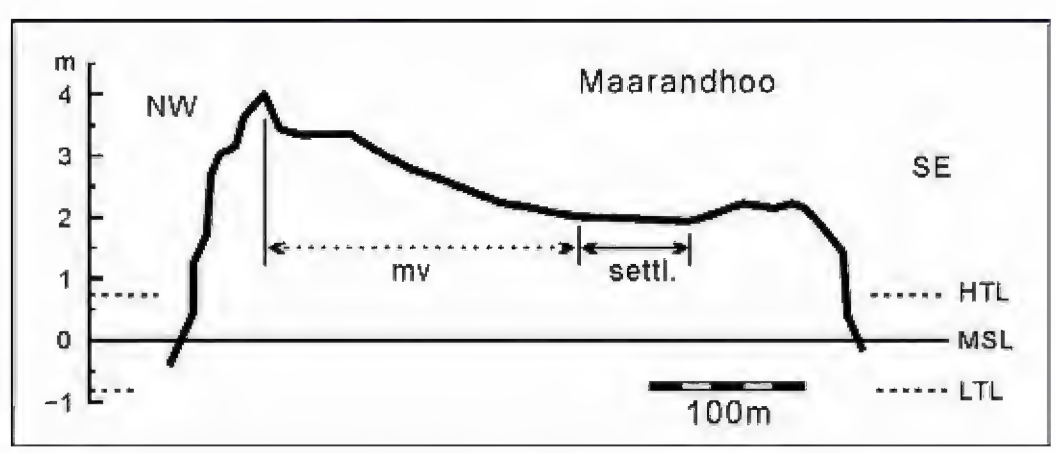

Figure 7. SE-NW profile of Maarandhoo (see Figure 6 for location). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, mv: matured vegetation, settl: settlement.

Photo 1. Erosion scarp, northern beach of Vashafaru (February 2005).

Photo 2. Watermark on the power plant wall, near the southern coast of Vashafaru (February 2005).

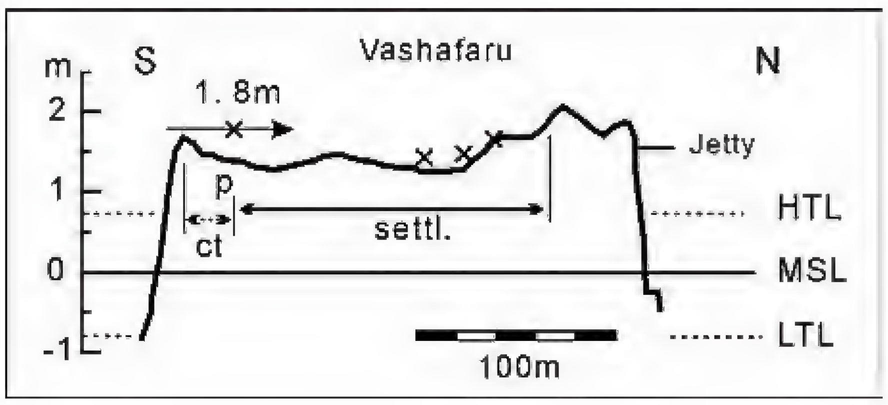

Figure 8. N-S profile of Vashafaru, Haa Alifu (see Figure 5 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, p: power plant, settl: settlement.

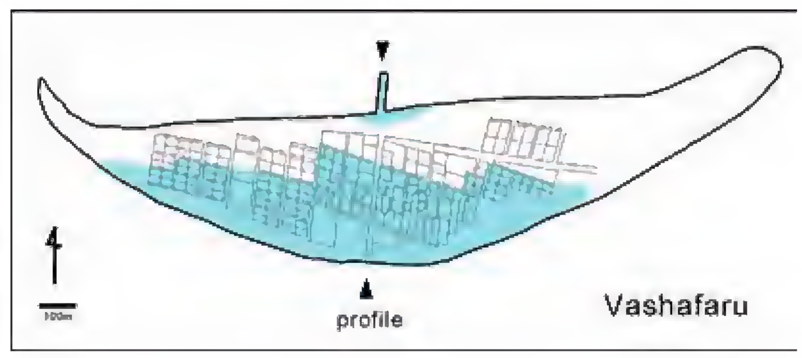

Figure 9. Inundation area of Vashafaru.

A wave from the southern atoll lagoon reached a height of 1.8 m above MSL, as estimated from a watermark on a wall beside the power plant at the southern coast (Photo 2). This wave ran over a beach ridge of 1.7 m above MSL and flowed into the lower lying inhabited area, inundating more than two-thirds of its area (Fig. 9). The height of the inhabited area is between 1.3 and 1.8 m above MSL (Fig. 8). Homes were inundated below floor level. Local residents talk of a scouring of 1.5 m depth cut into part of the southern beach ridge, although they had filled it in by February 2005.

Kelaa. Kelaa is an island 3 km long in a N-S direction located at the northeastern rim of a faro at the northeastern end of Haa Alifu Atoll. There is a village on the western side (lagoon side) of the northern part of the island. An E-W profile was measured across the village (Fig. 10). The width of the island is 1.1 km and a beach ridge of 2.7 m above MSL developed at the eastern end of the transect. A coconut forest formed behind the beach ridge. The heights underneath the coconut forest and in an inhabited area range between 1.6 and 1.9 m above MSL. A small beach ridge of 1.7 m above MSL formed at the western end. The slightly lower land that lies between the beach ridge and old village is a reclamation area, reclaimed in 1992 and used as a park and playground, with some new buildings.

The local residents reported the tsunami came from the southwest but did not reach the inhabited area. Scouring occurred at the western beach. Inundation occurred only at the southern (uninhabited) part of the island.

Filladhoo. Filladhoo developed at the eastern rim of a faro located on the eastern

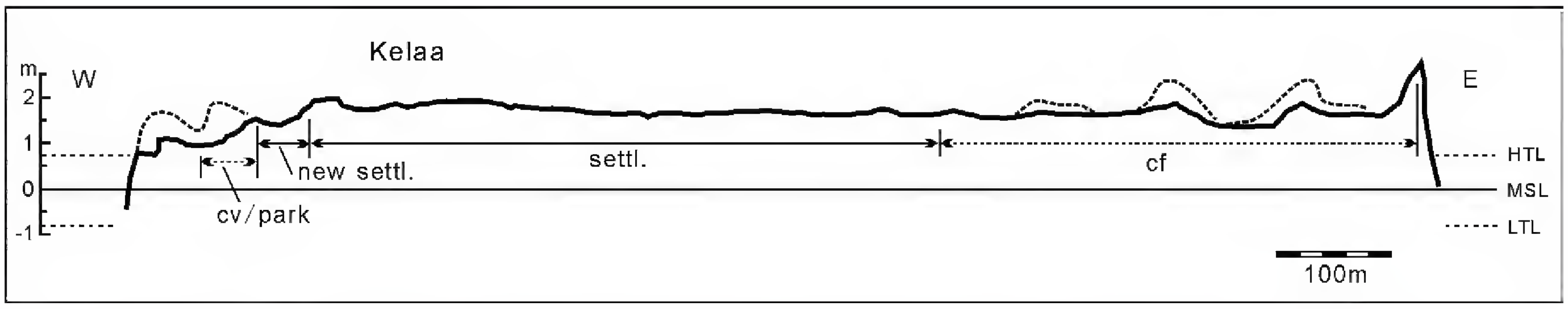

Figure 10. E-W profile of Kelaa, Haa Alifu (see Figure 5 for location). Dashed line indicates topographic relief near the transect. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cf: coconut forest, cv: coastal vegetation, settl: settlement.

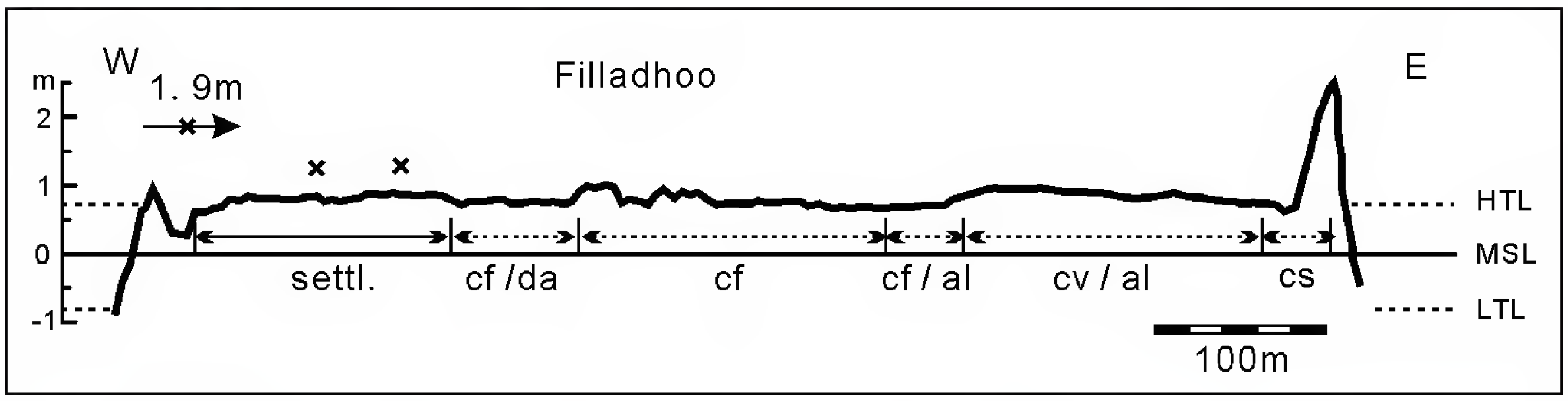

Figure 11. E-W profile of Filladhoo, Haa Alifu (see Figure 5 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, al: arable land, cf: coconut forest, cs: coastal shrub, cv: coastal vegetation, da: development area, settl: settlement.

side of the Haa Alifu Atoll. The maximum width of the island is at the southeast, and the village is located in the western part beside the lagoon. A NW-SE profile was measured across the village (Fig. 11). A beach ridge formed by coral rubble developed 2.5 m above MSL at the eastern end. The width of the beach ridge is 25 m, which is relatively narrower than for the other islands in Haa Alifu. There is coastal vegetation at the eastern one-third of the island at 0.7-to-0.9 m above MSL, and a coconut forest in the central one-third of the island at the same or slightly lower land level. The inhabited area is located at 0.6-to-0.9 m above MSL. A small beach ridge, formed by reef sand developed at the western coast, was partially eroded by scouring due to the tsunami.

The tsunami came from the northwest to inundate the entire village. A watermark at the fishery hut was 1.9 m above MSL. Eight homes that were completely destroyed faced the lagoon in the western part of the village.

Baarah. Baarah is a horse-shaped island developed at the eastern side of a faro in the eastern Haa Alifu Atoll (Fig. 12). A continuous beach ridge has developed on the eastern coast. A fresh to brackish water pond with mangrove forests formed behind the beach ridge along the eastern coast. The village is located at the western end beside the lagoon.

Local residents report that the tsunami first hit the village from the west (from the lagoon) and the entire inhabited area was inundated. A watermark in the western part of the village was 1.8 m above MSL. A destroyed wall (Photo 3) and scouring were observed at the western side of the island. Waves following the leading tsunami wave did not enter beyond the western beach. Tsunami damage on Baarah was extensive in the agricultural area but not in the inhabited area. The banana farm at the northwestern part of the island was inundated by the tsunami, causing 6,000 banana trees to wither.

Figure 12. Transects and direction of flood water on Baarah, Haa Alifu. Aerial photographs were taken in 1999 by the Maldive Government. a, b: photographic sites for Photos 3 and 4, respectively.

Photo 3. A collapsed wall at the lagoon-side on Baarah (February 2005).

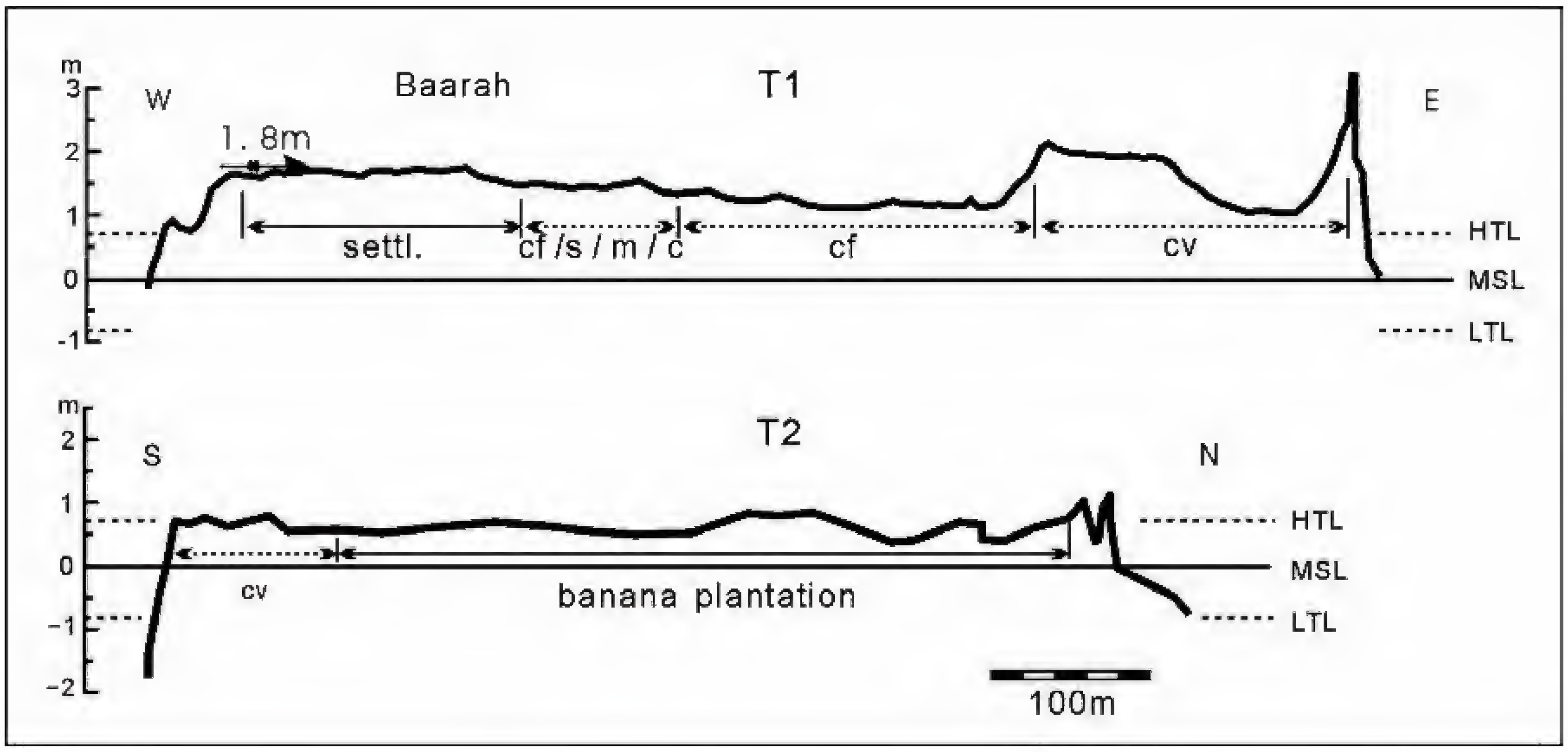

Figure 13. E-W profile (T1) and N-S profile (T2) of Baarah (see Figure 12 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, c: cemetery, cf: coconut forest, cv: coastal vegetation, m: mosque, s: school, settl: settlement.

Erosion due to the tsunami was observed at the northeastern coast from the east (Photo 4a, b). After the tsunami, beach sand moved landward to expose coral rubble (Photo 4c, d), and a tongue of sandy sediment accumulated in the mangrove area behind the beach ridge (Photo 4e, f).

Two topographic profiles were measured in Baarah. The E-W profile (T1) crossed the village in the central part of the island, and the N-S profile (T2) crossed the damaged banana farm at the northern part of the island.

The E-W profile (Fig. 13-T1) shows the beach ridge at the eastern coast reached 3.3 m above MSL. The topographic depression behind the beach ridge may represent a footprint of a pond. Another ridge of 2.1 m above MSL with coastal vegetation formed behind the depression. There is a mature coconut forest in the lower central area. The village was established at a topographic height of 1.5 to 1.7 m above MSL beside the lagoon.

The beach ridge is not well developed on the northern coast. The N-S profile (Fig. 13-T2) shows the coastal margin at northern Baarah is 1.1 m above MSL. There is a depression with a width of 180 m and height of 0.4-to-0.7 m above MSL behind the coastal margin. The banana farm lies in this section less than 0.9 m above MSL.

Coastal erosion was remarkable at the northeastern coast. However, the wave from the east caused no damage because the beach ridge acted as a retaining wall and the mangrove pond as a buffer zone. It is presumed that the tsunami entered the northern side of the faro and then the island from the northwestern coast where the beach ridge is undeveloped, thus inundating the banana farm.

Hanimaadhoo. Hanimaadhoo is located in northeastern Haa Dhaalu Atoll. Two E-W profiles were measured across the island (Fig. 14). A beach ridge exceeding 2.0 m above MSL developed at the eastern coast and another of 1.9 m at the western coast. No tsunami damage was reported on this island.

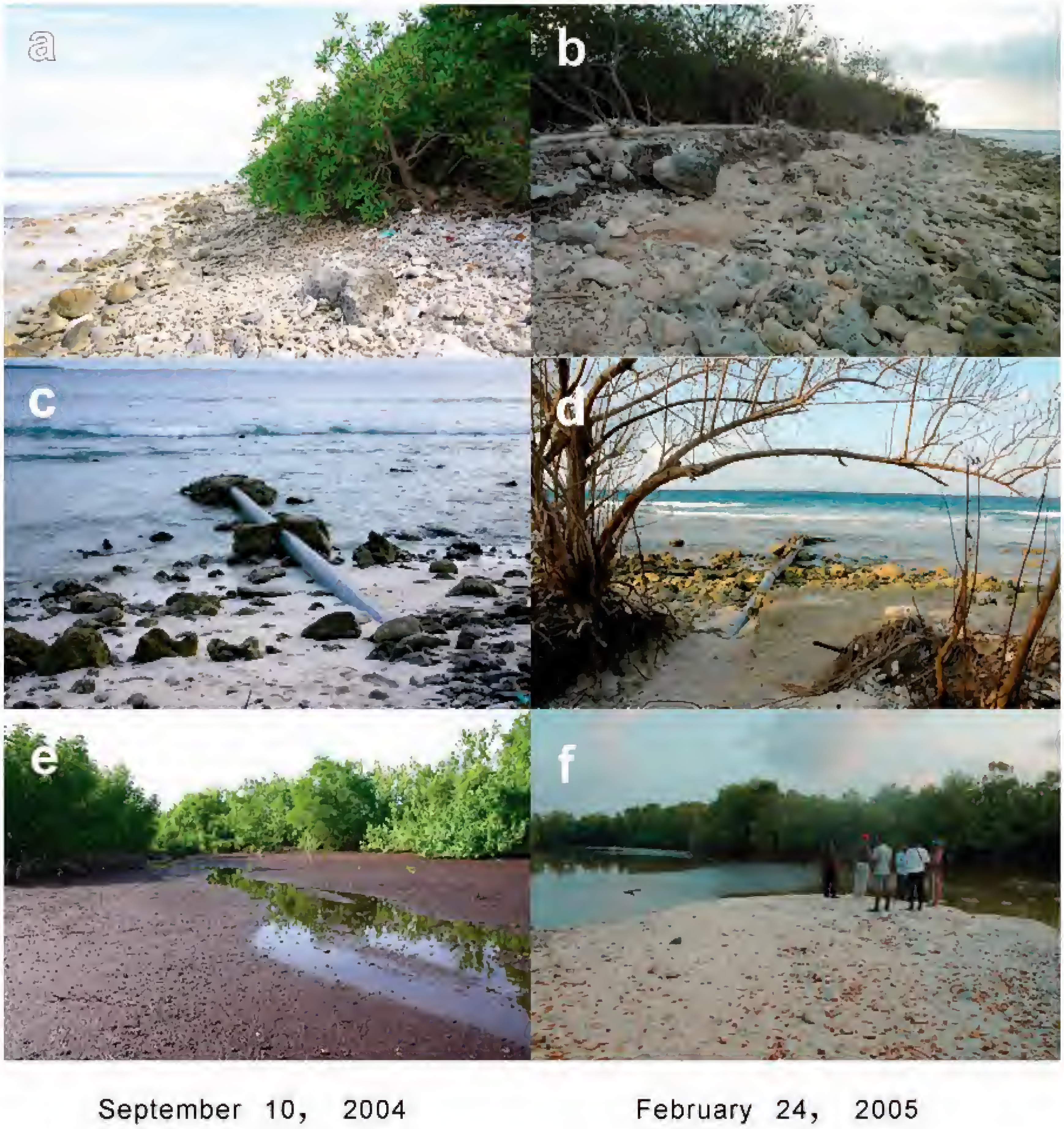

Photo 4. Post-tsunami geomorphological change at the northeastern coast of Baarah. Pre-tsunami photographs of September 10, 2004 (a, c, e) were taken by A. Nishan. a, b: erosion scarp and bared boulders at the beach ridge; c, d: erosion of sandy sediments at the beach; e, f: formation of tongues of sandy sediments at the mangrove swamp behind the beach ridge.

Nolhivaranfaru. The island of Nolhivaranfaru developed at the eastern side of a faro in Haa Dhaalu Atoll. According to local residents, the wave came from the lagoon (from the west or southwest), inundating the northern part of the island including most of the inhabited area. Along the western coast a collapsed wall (Photo 5) and large scouring of 1.2 m depth (Photo 6) indicates the considerable damage caused by the tsunami.

The measured profile (Fig. 15) shows a beach ridge of 2.0 m above MSL developed at the eastern coast. An 80 m-wide topographic height of 1.3 m above MSL formed behind the beach ridge which is covered by coastal vegetation. A mature coconut forest is sited in the lower central area. The village is located on the western side at a maximum altitude of 1.4 m above MSL. Watermarks on buildings showed the tsunami run-up height was around 1.4 m.

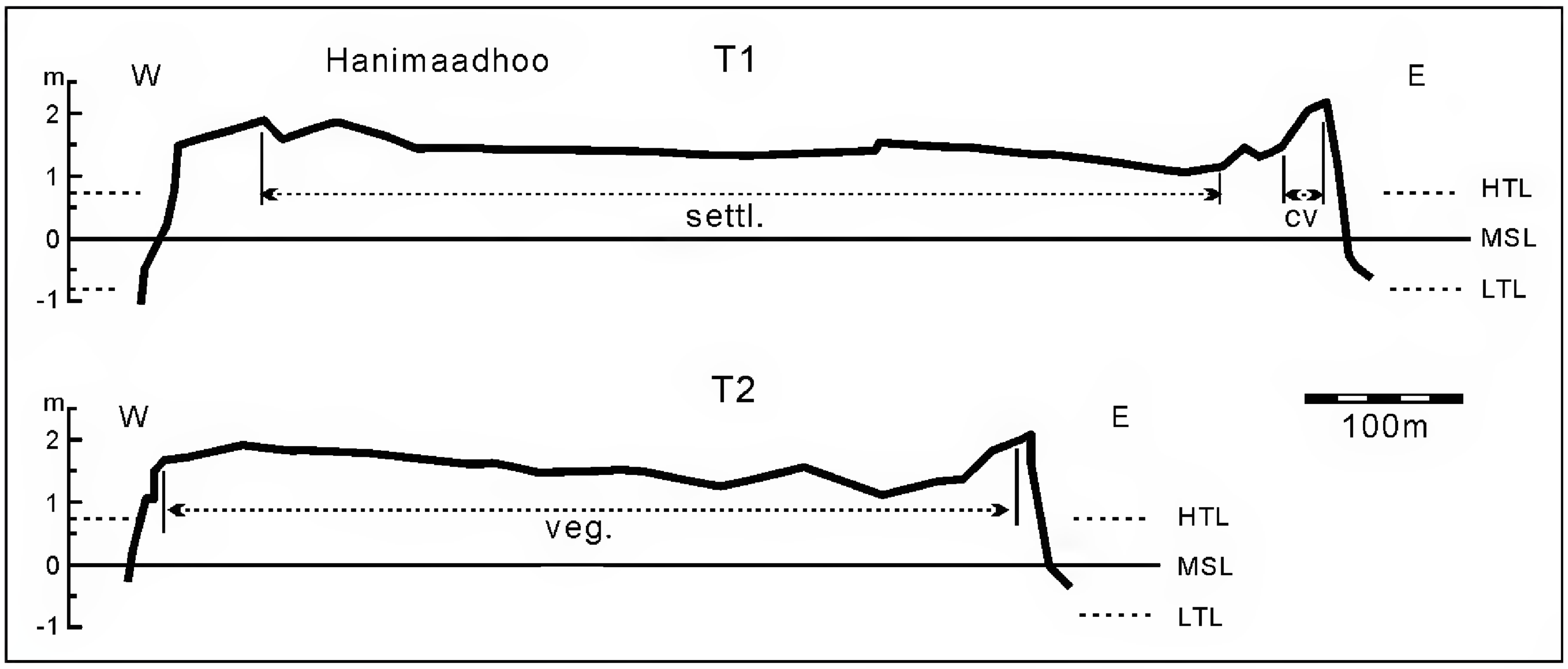

Figure 14. E-W profiles (T1 and T2) of Hanimaadhoo, Haa Dhaalu (see Figure 5 for location). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cv: coastal vegetation, settl: settlement, veg: vegetation.

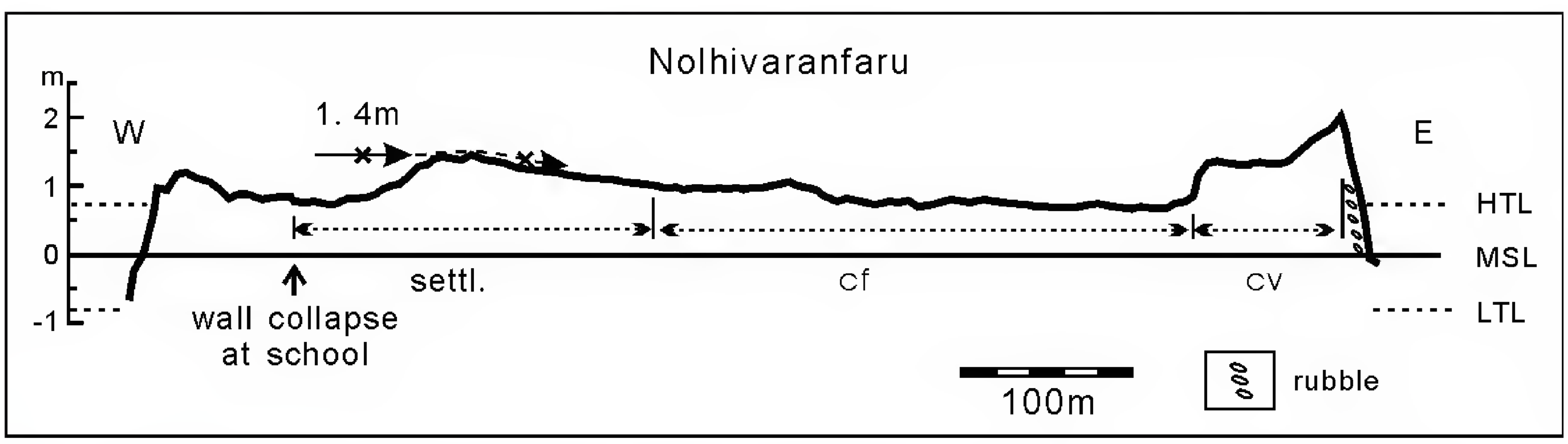

Figure 15. E-W profile of Nolhivaranfaru, Haa Dhaalu (for location see Figure 5). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cf: coconut forest, cv: coastal vegetation, settl: settlement.

Photo 5. A collapsed wall at the lagoon-side on Nolhivaranfaru (February 2005).

Photo 6. A scouring at the western coast of Nolhivaranfaru (February 2005).

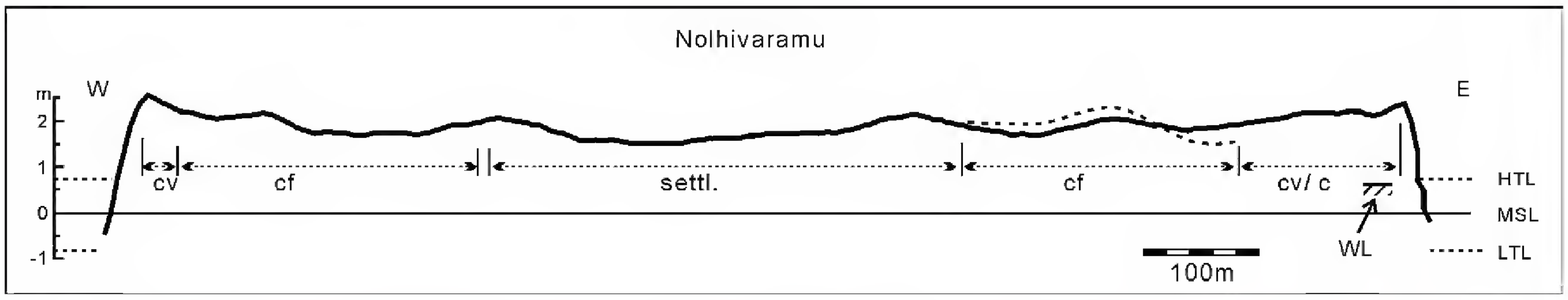

Figure 16. E-W profile of Nolhivaramu, Haa Dhaalu. Dashed line indicates topographic relief near the transect. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, c: cemetery, cf: coconut forest, cv: coastal vegetation, settl: settlement, WL: freshwater level at well (see text).

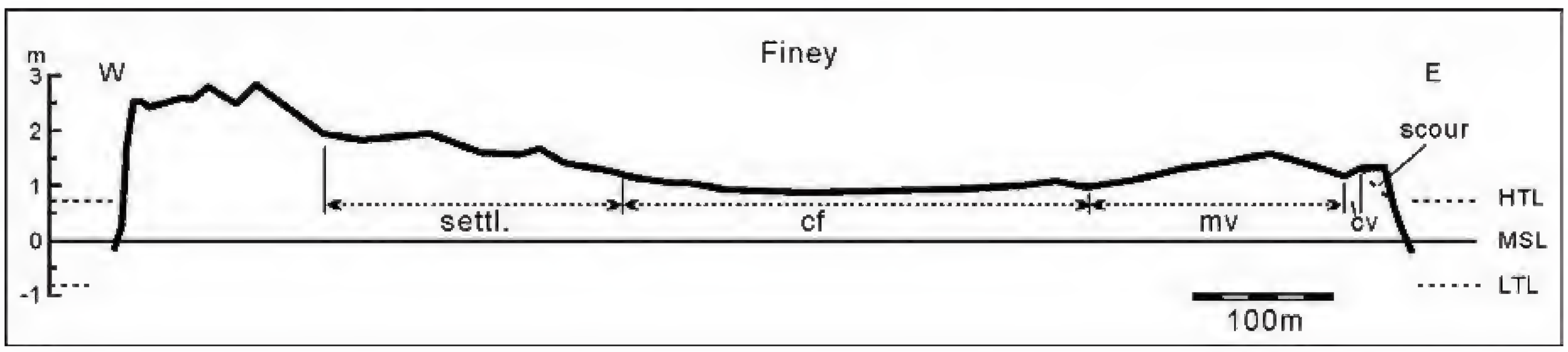

Figure 17. E-W profile of Finey, Haa Dhaalu. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cf: coconut forest, cv: coastal vegetation, mv: matured vegetation, settl: settlement.

Nolhivaramu. Nolhivaramu is an elliptical island wholly developed on the reef platform. A sand dune reaching an altitude of around 6 m has developed at the southeastern coast of the island. A large freshwater pond fringed by mangrove formed behind the sand dune.

An E-W profile of 1.1 km length across the central part of the island was measured along the road in front of the island office (Fig. 16). The village is located in the center of the island at an altitude 1.5 to 2.1 m above MSL. The village is surrounded by coconut forest which has the same land level as the inhabited area. In this section, beach ridges developed at the eastern coast at an altitude of 2.4 m above MSL and at the western coast at 2.6 m. There is a freshwater well located behind the beach ridge. The well water level was 0.6 m above MSL at 13:00 on February 23, 2004 under the tide level of 0.1 m above MSL. No tsunami damage was reported for this island.

Finey. Finey developed in the atoll lagoon and an E-W profile was measured on this island (Fig. 17). A sand dune of 2.8 m above MSL developed at the western coast. The height of the eastern coast is 1.6 m above MSL. A scouring was observed at the eastern coast. The central part of the island is relatively low lying with an altitude around 0.9 m. The tsunami entered the central depression of the island. The village is located west of the central depression at an altitude between 1.2 and 2.0 m above MSL. No damage was reported for the inhabited area.

Raa

The complete atoll chain of the Maldives forms two lines from latitude 2°40´ to 6° N (see Figure 3-2). Raa Atoll (North Maalhosmadulu Atoll, Figure 3-1) is 28 km in the E-W direction and 65 km in the N-S direction at the northwestern end of the double atoll

Figure 18. Location of transects on Ifuru and Ugulu, Raa. The satellite image is provided by Google Earth.

chains. The atoll consists of many faroes. It

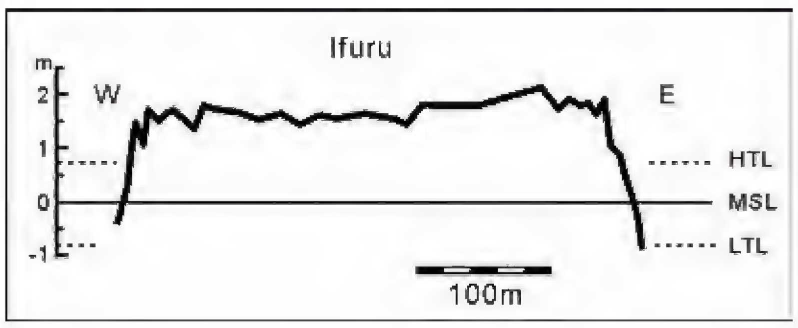

Figure 19. E-W profile of Ifuru (for location see Figure 18). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

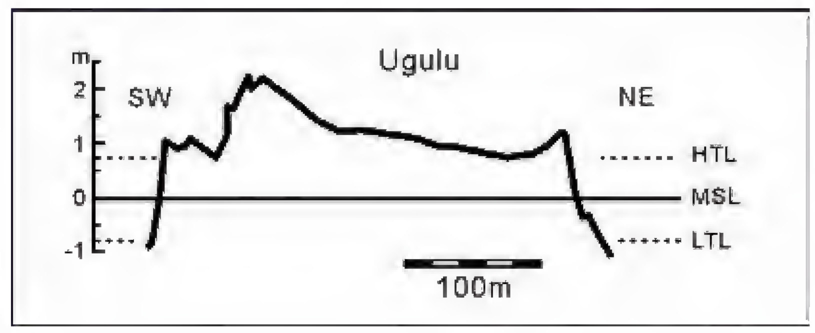

Figure 20. NE-SW profile of Ugulu (for location see Figure 18). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

lies north of Baa Atoll, separated by the "Hani Kandu" channel. Four islands including two uninhabited islands were surveyed at Raa Atoll.

Ifuru. Ifuru is an uninhabited island located at the eastern rim of Raa Atoll (Fig. 18). The height of the island lies between 1.6 and 1.9 m above MSL along the measured profile in an E-W direction (Fig. 19). No clear marks of the tsunami were found on the island.

Ugulu. Ugulu is another uninhabited island, located south of Ifuru (Fig. 18). A profile in a NE-SW (45°-225°) direction was measured at the northern part of the island (Fig. 20). A sand dune with the height of 2.2 m above MSL formed on the western side of the island. No clear marks of the tsunami were found on the island.

Kandholhudhoo. Kandholhudhoo is an inhabited island of 280 m in the E-W direction and 530 m in N-S direction, located in a channel in the western Raa Atoll (Fig. 21). The island has been expanded by land reclamation all around the natural island and is surrounded by sea walls. The inhabited area is located in the central part of the original island, at a height of between 1.1 to 1.9 m above MSL (Fig. 22). The sea wall height is around 1.0 m above MSL and the height of the reclaimed land lies below 1.0 m. The watermarks became higher to the west, 2.7 m above MSL at maximum. The island was the most badly affected among the islands in the northern Maldives. Three people died and most of the residents took refuge on other islands.

Meedhoo. A NE-SW(20°-200°) profile was measured at Meedhoo located in Raa lagoon (R-13 in Figure 3-1). The island height is around 1.4 to 1.5 m above MSL except for slightly higher ground at 1.7 m at the southern part (Fig. 23). No serious damage was reported from this island.

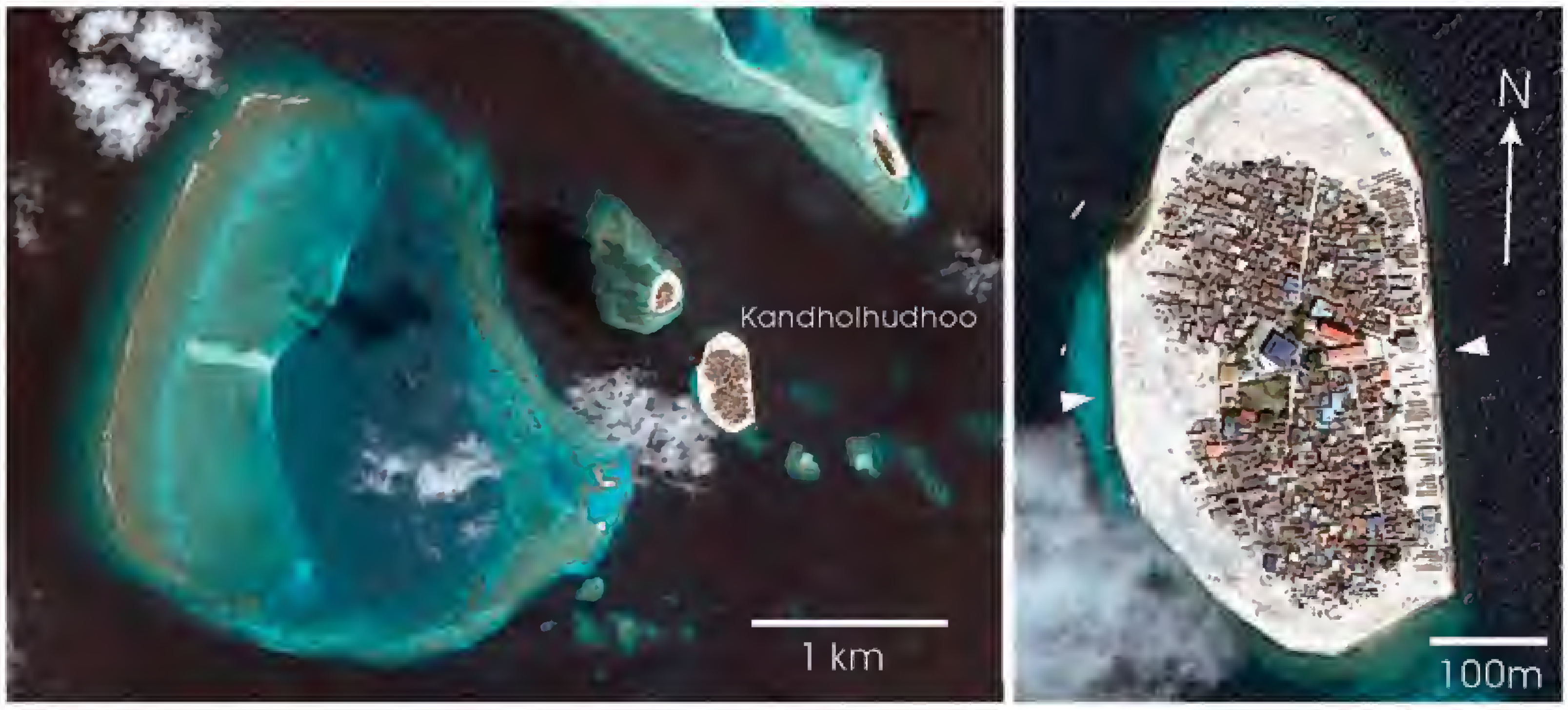

Figure 21. Location of transect on Kandholhudhoo, Raa. The satellite image is provided by Google Earth.

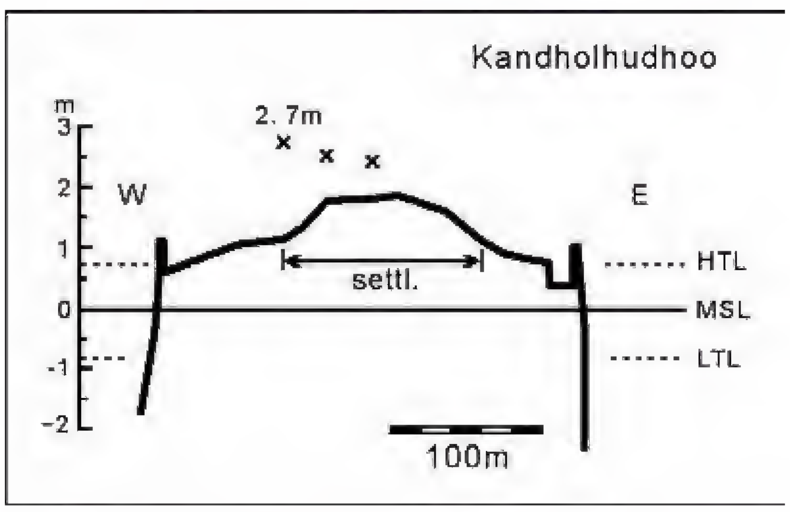

Figure 22. E-W profile of Kandholhudhoo. X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

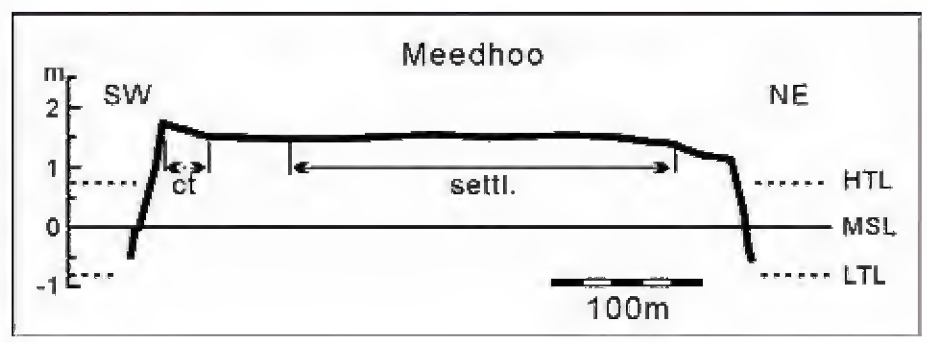

Figure 23. NE-SW profile of Meedhoo, Raa. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, settl: settlement.

TSUNAMI DISASTER AND ISLAND TOPOGRAPHY IN THE CENTRAL MALDIVES

Kaafu

Kaafu Atoll (3°49' to 4°59' N, 3°20' to 73°43' E) is an administrative district around the capital Malé in the central Maldives. It consists mainly of two large atolls: North Malé Atoll (43 km E-W, 60 km N-S) and South Malé Atoll (21 km E-W, 35 km N-S, see Figure 3-2). In these atolls, interrupted atoll rims separated by channels form the eastern rims, and faroes form the western rims. One inhabited island on North Malé Atoll and two inhabited islands on South Malé Atoll were surveyed.

Dhiffushi. Dhiffushi is an island, 1 km N-S by 250 m E-W, located at the eastern end of North Malé Atoll. A harbor was constructed at the eastern coast by dredging the reef flat, and the island was expanded at the eastern and northwestern sides by land reclamation using dredged sand (Fig. 24).

Spurs and groove topography has developed in water depth of < 3 m at the outer reef edge. The outer reef slope deepens with a gentle slope from -3 to -9 m, followed by a steep drop-off. Large boulders of 1-to-2 m in diameter were located in rows in shallow

Figure 24. Location of transect (white arrows) on Dhiffushi, Kaafu (North Malé Atoll). Aerial photographs were taken in 1999 by the Maldive Government. The area reclaimed after 1999 is shown in yellow.

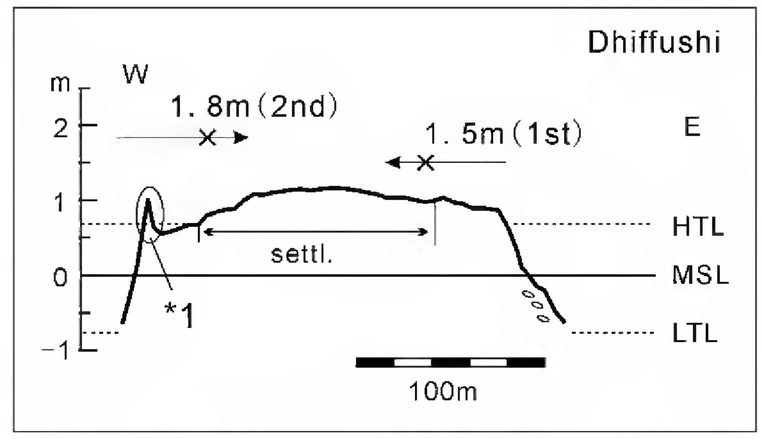

Figure 25. E-W profile of Dhiffushi (for location see Figure 24). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement , *1: ridge partially destroyed by scouring.

grooves above a 3 m depth (Photo 7a). A fisherman told us that these boulders were not there before the tsunami. The maximum diameter of the boulders was 2.5 m and they were distributed in a spurs and grooves zone at water depth of less than 3 m. Reef blocks and debris from collapsed buildings accumulated along the eastern coast of Dhiffushi (Photo 7b). Damage to harbor facilities was also observable (Photo7c).

An E-W profile was measured in Dhiffushi (Fig. 25). Most of the inhabited area is located between 1.0 and 1.2 m above MSL, with some houses sited below 0.7 m at the lagoon front. The leading tsunami wave came from the east. Local residents reported it reached 50 cm above the road level (1.5 m above MSL) and watermarks support these reports (Photo 7d). Along the western side (lagoon-side) of the island, some scouring furrows were observed under coconut trees behind the beach. At the time of study, these furrows (dashed line in Photo 7e) had been buried by debris brought by local residents. Beach erosion was observed at the foot of coconut trees (Photo 7f), although there were no signs of beach retreat. Seawater now flows into the inhabited area at the front of the lagoon through eroded hollows at high tide. Many walls collapsed along the lagoon front (Photo 7g). Watermarks and accounts from local residents indicate the tsunami reached 1.05 m above the road level (1.8 m above MSL) along the western coast (Photo 7h, i).

Local residents told us that the tsunami initially surged from the east, then from the west 30 minutes later. The higher wave came from the west, from the lagoon. This account agrees with the measured watermarks, 1.5 m above MSL in the east and 1.8m in the west. Severe damage occurred to buildings and walls in the western part of the island.

Maafushi. Maafushi is an island 1.4 km long and 270 m wide with the long NE-SW axis developed at the eastern rim of South Malé Atoll (Fig. 26). A small ridge of 1.4 m above MSL with coconut trees has formed along the eastern coast (Fig. 27). Some parts of this ridge were eroded by scouring (Photo 8a). Homes in a block in the inhabited area were completely destroyed along the eastern coast (Photo 8b). The height of the inhabited area is around 1.0 to 1.2 m above MSL.

Photo 7. Post-tsunami photographs of Dhiffushi (February 2005). a: reef blocks arranged in a row in a reef edge groove of 3 m depth, on east Dhiffushi; b: harbor debris at the eastern coast; c: harbor damage at the eastern coast; d: watermark near the eastern coast; e: scouring (dashed line) at the western (lagoon-side) coast filled in with debris by the residents; f: beach erosion at the western coast; g: destroyed wall at the western coast; h, i: watermark near the western coast.

Figure 26. Location of transect and photographic site at Maafushi, Kaafu (South Malé Atoll). The satellite image (January 2, 2005) is provided by Digital Globe. a-d: photographic sites for Photo 8.

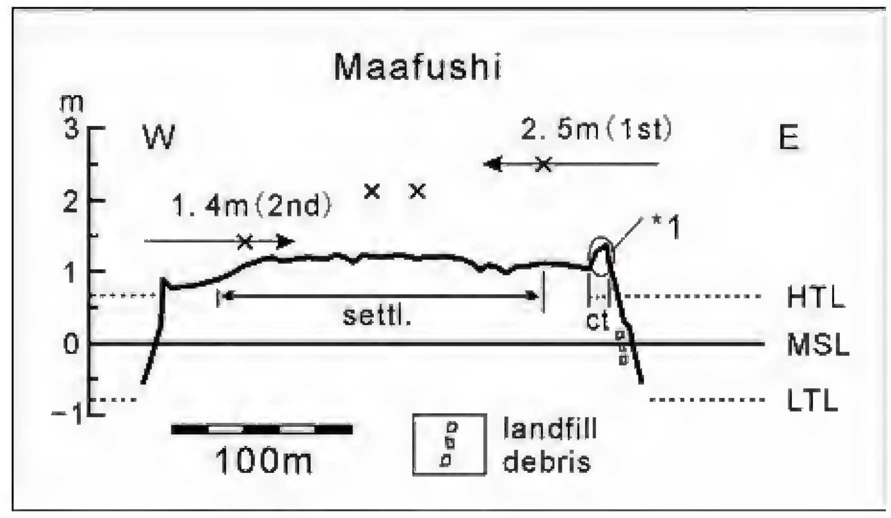

Figure 27. E-W profile of Maafushi (see Figure 26 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, settl: settlement, *1: ridge partially destroyed by scouring.

Residents reported that the tsunami came from the east, increasing in height and reaching a maximum level 3-to-4 minutes after the leading wave arrived. The second flood water came from the west, 15 minutes after the first tsunami from the east. A watermark in the easternmost house was 2.5 m above MSL. Watermarks on walls and shop windows in the center of the island were around 2.0 m above MSL (Photo 8c), and on walls at the lagoon side around 1.4 m above MSL. Tsunami run-up heights were estimated to be 2.5 m above MSL from the east and 1.4 m above MSL for the second wave from the west. Part of the harbor facilities were also damaged on the western coast (Photo 8d).

Guraidhoo. Guraidhoo is an island, 0.8 km N-S by 0.5 km E-W, located between two channels at the southeastern rim of South Malé Atoll (Fig. 28). A profile was measured across the island from the southeast to the northwest. The island topography is flat and there is no beach ridge at either the eastern or western coast (Fig. 29). The inhabited area lies 0.7 to 1.0 m above MSL. Homes in a block in the inhabited area were completely destroyed along the eastern coast (Photo 9a).

According to local residents, the first tsunami from the east was the highest and caused severe damage. A watermark on a wall in a living room in the easternmost house was found 2.4 m above MSL (Photo 9b). Two waves then arrived from the northwest (from the lagoon) 15 and 30 minutes after the tsunami from the east. The run-up heights of these waves were lower than the first tsunami from the east, with the second wave from the NW being the lowest. A watermark on a wall at the western coast was 1.6 m above MSL.

A dhoni (fishing boat) was run up the beach (Photo 9c) and many walls collapsed (Photo 9d) along the western coast. Damage along the lagoon coast was worse than on Maafushi. The higher run-up height and lower land level (ca. 0.2 m lower than Maafushi) appears to be the reason for extensive damage along Graidhoo's western coast.

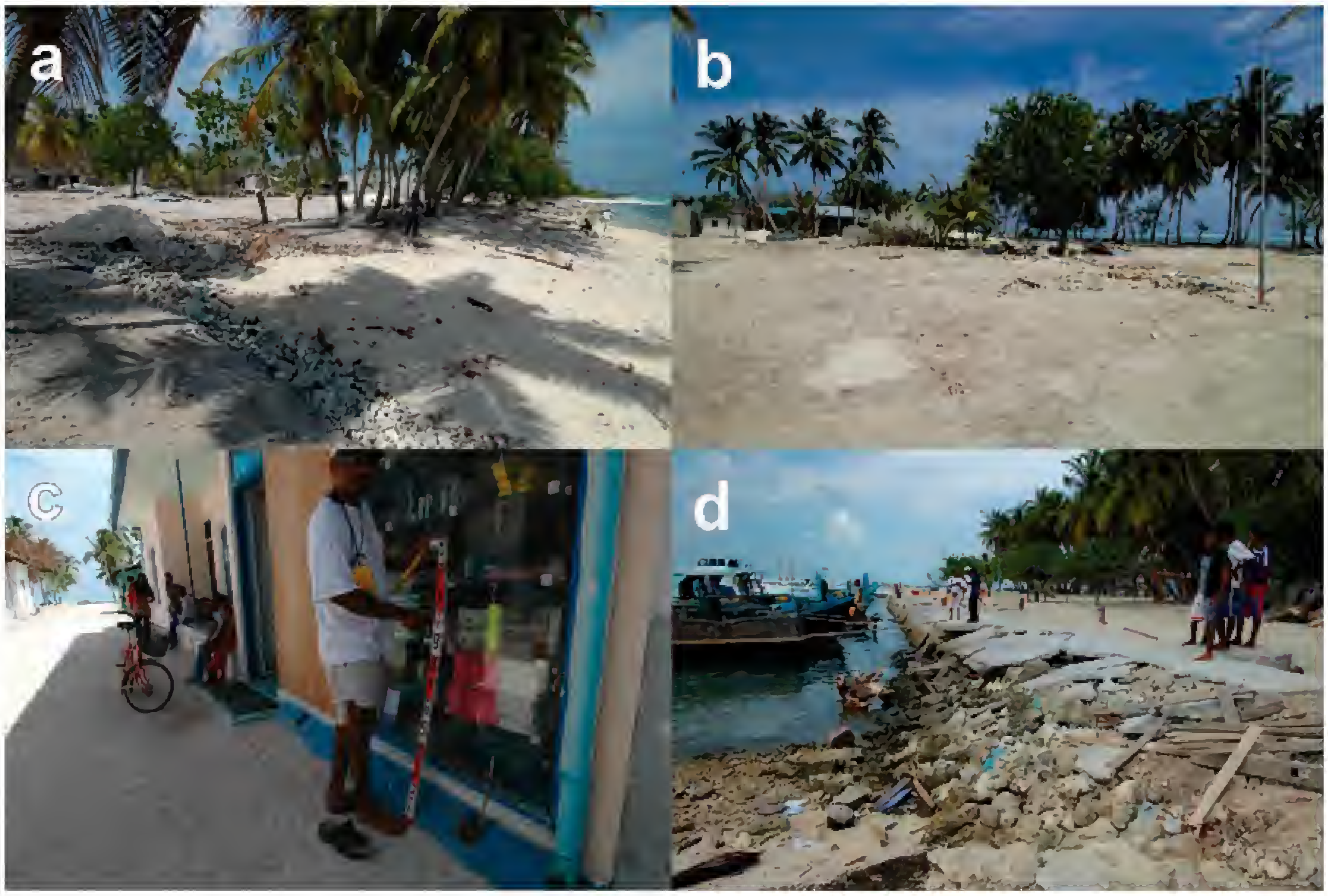

Photo 8. Post-tsunami photographs on Maafushi (February 2005). a: scouring at the eastern coast; b: settlement area completely destroyed at the eastern coast; c: watermark at the center of the island; d: harbor damage at the western coast.

Malé

Malé, the capital of the Republic of Maldives, is located at the southeastern part of the North Malé Atoll (Fig. 3-2). The island is 1.2 km N-S and 2 km E-W, with an area of 2.0 km^2. The island's original area of 1.1 km^2 was expanded by land reclamation due to its increasing population. Following a high-tide disaster in April 1987, when 48% of the island was inundated and 360,000 m^3 of reclaimed sand was washed away (Uda 1998), sea walls surrounding the island were constructed using foreign aid from the Japanese Government. Work was completed in 1990. Two-thirds of the island area was temporarily inundated by the Indian Ocean Tsunami, as shown in Figure 30. The destructive damage reported on other islands, such as building collapse in the coastal areas, did not occur on Malé because the sea wall acted as a breakwater (Ohtani et al., 2005).

Vaavu

Vaavu Atoll (Felidhe Atoll) is an atoll of 52 km in the E-W direction and 42 km in N-S direction, located south of South Malé Atoll between 3°13' and 3°41' N, 73°17' and 73°46' E (Fig. 3-2). The discontinous atoll rim (Fig. 31) consists of many faroes except in the southeastern part of the atoll.

Thinadhoo. Thinadhoo is located on a reef between passes connecting the ocean with the lagoon in eastern Vaavu Atoll. A profile in the NNE-SSW direction was measured along a road across the village (Fig. 32). The height of island is 1.0 to 1.2 m

Figure 30. Non-inundated area (yellow) in the capital Malé. The satellite image (January 2, 2005) is provided by Digital Globe.

above MSL in the central inhabited area and 1.4 m in coastal areas.

According to Mr. Mohamed Naeem of the island office, the tsunami entered the island at 9:15 from the northeast and east at the same time, and flooded the island 1.2 m above road level. Three other waves then hit the island from the southwest (from the lagoon) about 4 minutes after the first tsunami wave. The first two of these three waves reached 0.6 m above the jetty. The last wave was lower and not significant.

While a house was partially destroyed and many walls collapsed, there were no injuries reported on Thinadhoo. All of the inhabited area except the school at the southern end of the village was inundated. Water reached 0.9-to-1.05 m inside homes. Residents had already removed watermarks inside their homes by September 1, 2005.

TSUNAMI DISASTER AND ISLAND TOPOGRAPHY IN THE SOUTHERN MALDIVES

Meemu

Meemu Atoll (Mulaku Atoll) is an atoll of 30 km in the E-W direction and 48 km in the N-S direction, located from 2°45' to 3°10' N, 73°22' to 73°39' E (Fig. 3-2). The atoll suffered extensive damage. Ten islands including two uninhabited islands were surveyed in Meemu Atoll.

Maduvvari. Maduvvari is located at the northern rim of Meemu Atoll (Fig. 33). The southeast 140 m of the 450 m profile was measured across the island in a NE-SW direction is reclaimed land. The land level lies at 0.7 to 1.2 m and is higher in the northeastern area (Fig. 34). Most of the island area is inhabited. Watermarks were higher in the northeast, at 1.6 m above MSL at maximum.

Raiymandhoo. According to Mr. Ahmed Mufeed, the Island Chief (Katheeb) of Raiymandhoo, which is located at the northeastern rim of Meemu Atoll (Fig. 33), the

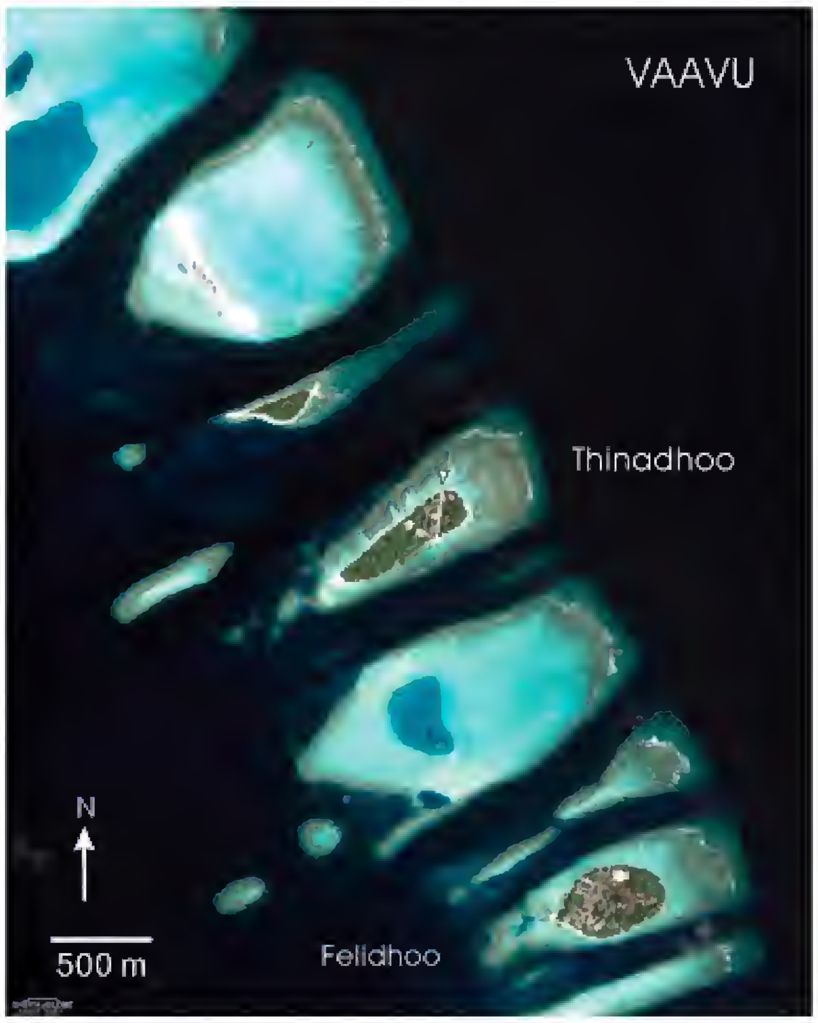

Figure 31. Eastern atoll rim of Vaavu and location of transect on Thinadhoo. The satellite image (January 2, 2005) is provided by Digital Globe.

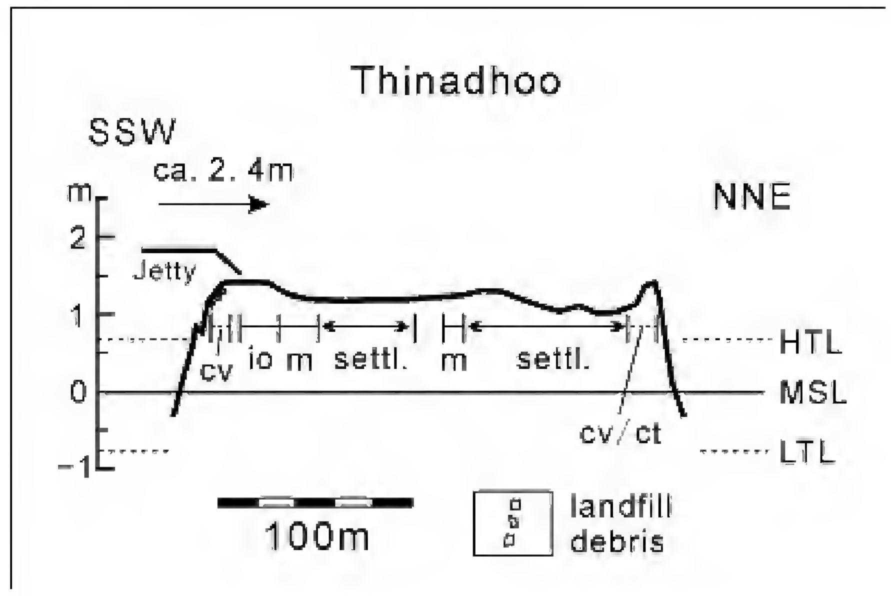

Figure 32. NEN-SWS profile of Thinadhoo (see Figure 31 for location). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, cv: coastal vegetation, m: mosque, io: island office, settl: settlement.

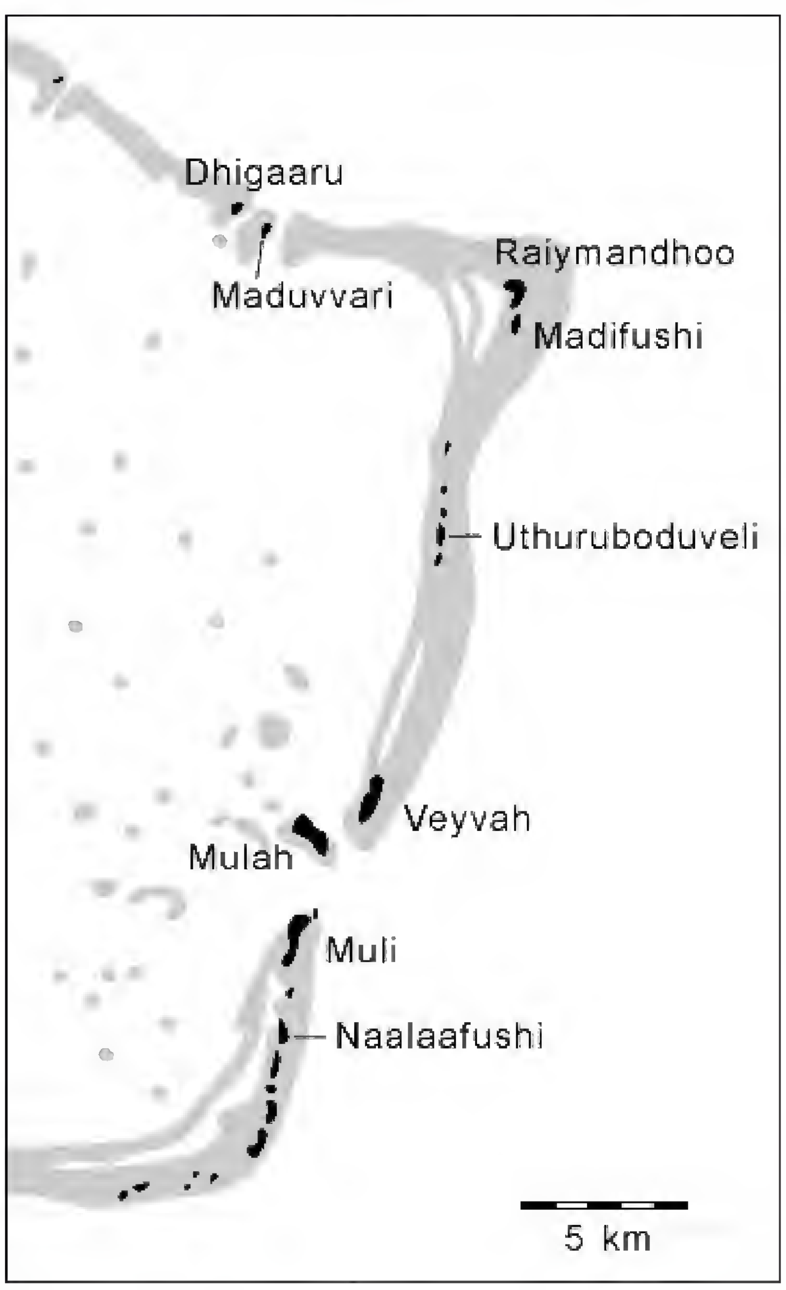

Figure 33. Location map of the eastern Meemu Atoll

tsunami arrived from the northeast and east. The island was inundated 1.2 m above the road level. Another wave arrived from the west 15 minutes later, at around knee height at the beach and broke in front of the beach.

An antenna facility for mobile phones at the northeastern coast was damaged (Photo 10) and walls were destroyed in a village on the western coast. Most of the island was inundated except for the old graveyard in the center of the island. Nobody was washed out into the lagoon.

An E-W profile was measured on this island. The altitude is between 0.9 to 1.3 m above MSL and is slightly higher in the eastern part (Fig. 35). The inhabited area is located in the western (lagoon-side) third of the island. In the central third, there is coconut and pandanus forest, and in the eastern third there is coastal vegetation. The water level was observed to be higher in the east, at a maximum of 2.3 m above MSL.

Madifushi. Madifushi (Fig. 33) suffered extensive damage in the tsunami and the entire population was relocated to Maamigili in Alifu Dhaalu (South Ari Atoll). At the time of study, the remains of buildings were still apparent (Photo 11). A clock in the island office stopped at 9:09 (Photo 12). Mr. Ahmed Mufeed, the

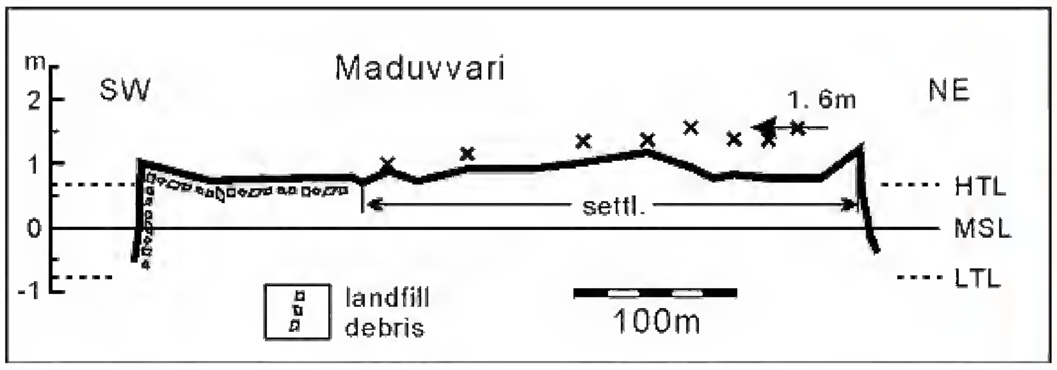

Figure 34. NE-SW profile of Maduvvari, Meemu (see Figure 33 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

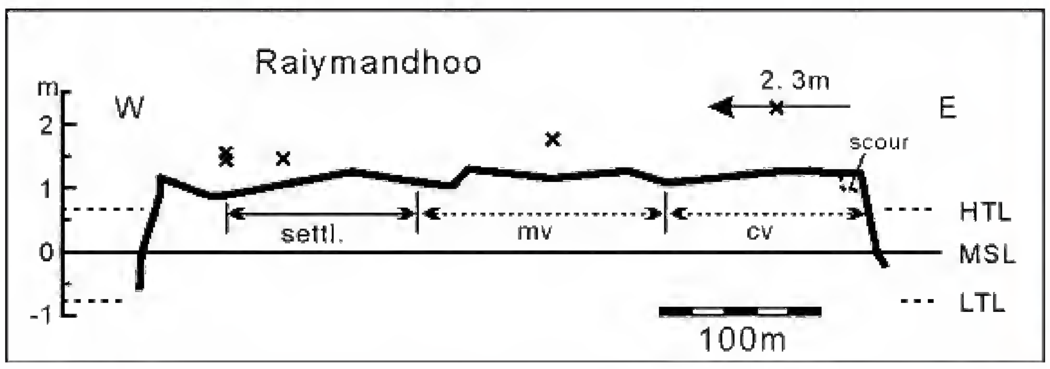

Figure 35. E-W profile of Raiymandhoo, Meemu (see Figure 33 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cv: coastal vegetation, mv: matured vegetation, settl: settlement.

Photo 10. Damaged telecommunication facility at the northeastern side of Raiymandhoo.

Island Chief of Raiymandhoo, guided us around the island and reported what happened there.

Two people died on Madifushi, one a local resident and the other a foreign contractor dredging the harbor. The local residents ran to safety from the tsunami surge over a reclaimed land causeway to Raiymandhoo. The causeway collapsed and washed away just after the last resident had crossed.

A profile was measured along the southern street of the former village. The altitude of the island lies between 0.8 and 1.2 m above MSL. It is higher in the east where there is a coconut forest in the eastern 50 m zone (Fig. 36). The western side of the village is relatively low, at 0.8 m above MSL. People ran to escape the seawater in coconut trees at the western coast where the altitude is around 1.0 m above MSL. Of the 6 watermarks we observed on houses, the higher marks were in the east with a maximum height of 2.2 m above MSL. Aside from these watermarks, a parabolic antenna which stands higher than a house roof was damaged (Photo 13), possibly indicating that flying debris reached 5 to 6 m in height instantaneously.

Uthuruboduveli. Uthuruboduveli is an uninhabited island 80 m wide located on the eastern rim of Meemu Atoll (Fig. 33). The island was separated into pieces near the southern end by tsunami erosion. The height of the island is 1.0-to-1.2 m above MSL (Fig. 37). A watermark on a tree trunk indicated the water level reached 1.5 m above MSL.

Veyvah. Veyvah is 330 m wide and is located on the eastern rim of Meemu Atoll (Fig. 33). The altitude is 0.6-to-1.2 m above MSL (Fig. 38) and the inhabited area is located in the central low-lying part of the island.

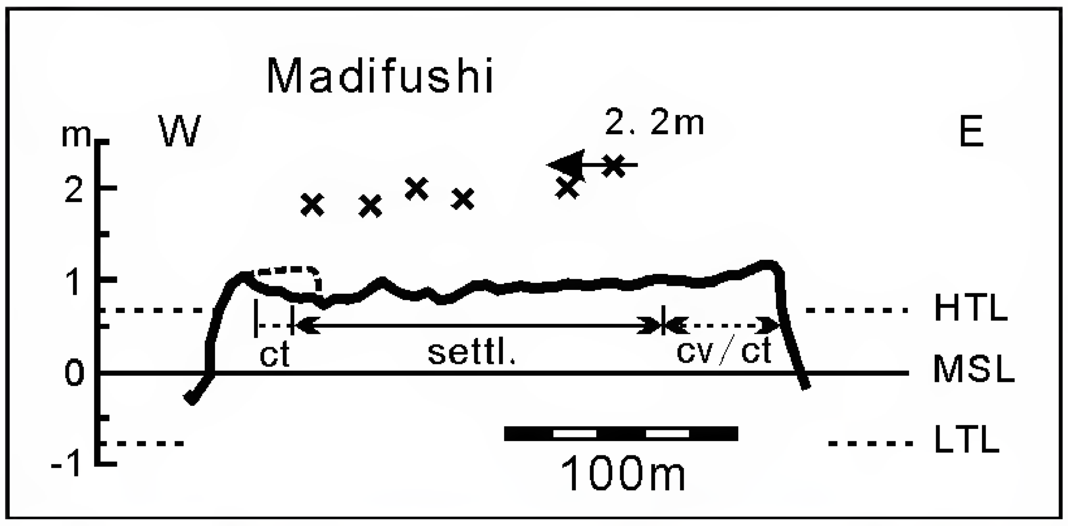

Figure 36. E-W profile of Madifushi, Meemu (see Figure 33 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, cv: coastal vegetation, settl: settlement.

Photo 11. Debris remains untouched on Madifushi (August 2005).

Photo 12. Clock in the island office stopped at the time of tsunami on Madifushi (March 2005).

Local residents reported that 10 minutes after the sea surface was seen to bubble, the tsunami arrived from the east as a raised sea level. Then flood water twice arrived from the west. Watermarks indicated a run-up height of 1.7 m above MSL on both the east and the west sides of the island. The tsunami seems to have entered the "Mulah Kandu" channel, which cuts the eastern atoll rim south of Veyvah, and then entered the western side of the island. In Mulah, south of "Mulah Kandu", local residents told us that the tsunami entered from the east and backwashed to the ocean off Mulah as described later. This backwash may then have rushed to the western coast of Veyvah.

Mulah. Mulah is the only island in Meemu Atoll that is located in a channel opening eastward (Fig. 33). A 470-m long profile was measured from NNE to SSW along the short axis of the island (Fig. 39). The altitude lies between 0.5 and 1.2 m above MSL and is lowest in the central part of the

Photo 13. Deformation of parabolic antenna on Madifushi (March 2005).

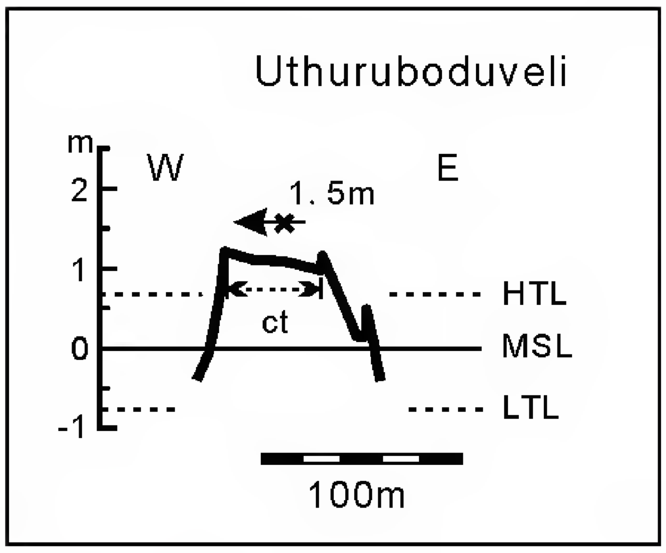

Figure 37. E-W profile of Uthuruboduveli, Meemu (see Figure 33 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees.

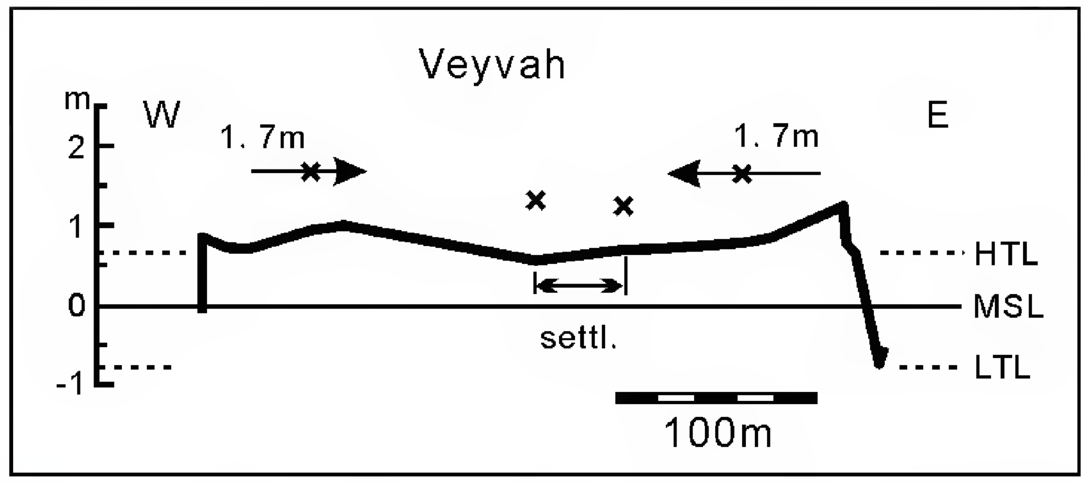

Figure 38. E-W profile of Veyvah, Meemu (see Figure 33 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

Figure 39. Location of transect at Mulah, Meemu. The satellite image is provided by Google Earth.

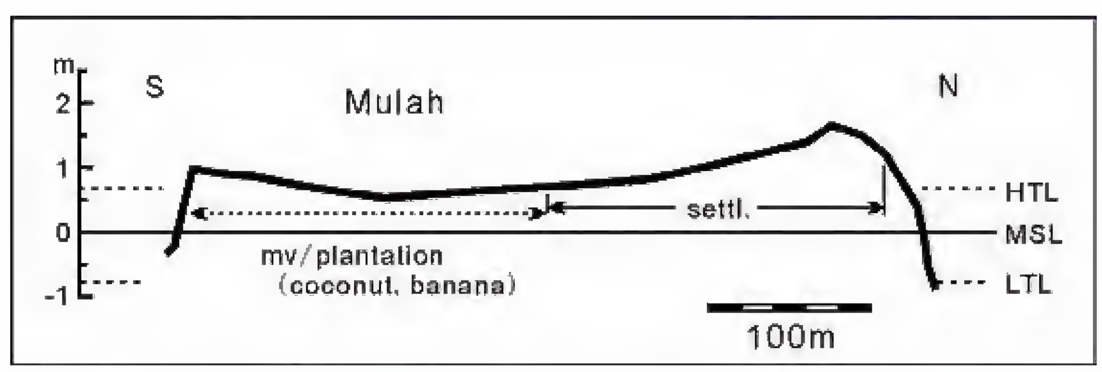

Figure 40. N-S profile of Mulah (for location see Figure 39). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, mv: matured vegetation, settl: settlement.

island (Fig. 40). The inhabited area is located at the northern part of the island.

Local residents reported that they heard loud noises 2-to-4 minutes prior to the tsunami. Before the tsunami arrived at Mulah, the island chief announced that Naalaafushi had been hit by a tsunami. In Meemu Atoll, the tsunami surged to Naalaafushi earlier than to other islands. The information about the tsunami was first disseminated from Muli, the atoll capital, by mobile phone and then from Muli to other islands by mobile phone thereafter. After the announcement of the tsunami, the local residents of Mulah went to the northeastern beach, where the harbor is located, to see the tsunami. The residents saw white bubbles rushing in from the ocean over a long distance.

The tsunami rushed to the island from both the northeast and the southwest. Mulah is located in the center of the eastern Meemu passage facing two channels, the northern "Mulah Kandu" and southern "Mulee Kandu" channels. Local residents who were on the northeastern beach when the tsunami hit, say the tsunami entered from the east with white bubbles, reached as far as the village, then backwashed to the outer sea. If this account is

accurate, the tsunami entered only at the entrance to the reef passage, not into the whole lagoon area of Meemu Atoll.

In Mulah, the run-up height reached 0.6 m above the jetty and reached the foot of houses at the beach-front area, but did not inundate them. The second wave reached around knee level at the shore. In contrast, floodwater from the southwest entered the island and homes beside a road near the southwestern coast were inundated slightly. Local people remember no particular time lag between the waves from the northeast and the southwest. There were no dead, no injured and no building damage on Mulah.

Muli. Muli (Fig. 41) is the capital island of Meemu Atoll where a transverse profile was measured across the island from east-to-west (Fig. 42). The eastern 75 m of the 330 m profile is reclaimed land. Urbanization is progressing in Muli where housing sites are planned on reclaimed land in order to receive immigrants from other islands. The altitude of the island is between 1.0 and 1.2 m above MSL. The eastern reclaimed land is 0.1-to-0.3 m higher than the original island. Watermarks remained on homes that are higher in the east, at 2.6 m above MSL at maximum.

Mr. Moosa Nasser, the island chief of Muli, informed us of the situation during the tsunami and at the time of this study (Photo 14). Residents heard a loud noise and saw bubbling sea water on the eastern reef-flat two minutes prior to the tsunami. The wave reached waist level. One minute later, two more waves reaching 2.4 m rushed in from the east. No flood water from the lagoon was reported on this island.

Figure 41. Location of transect at Muli, Meemu. Hatched area was completely destroyed. The satellite image is provided by Google Earth.

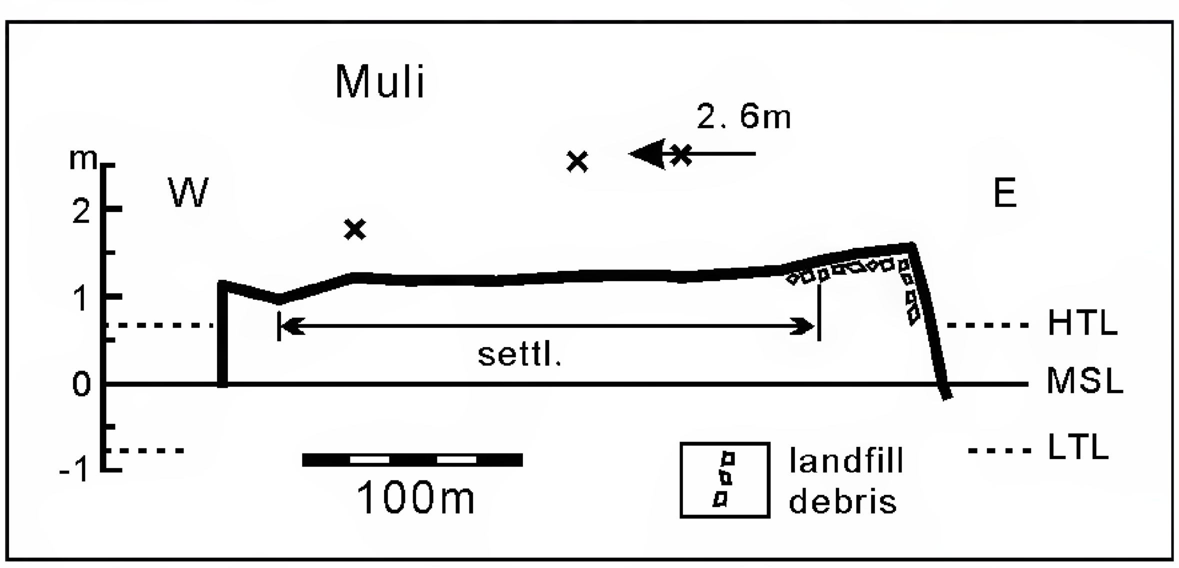

Figure 42. E-W profile of Muli (for location see Figure 41). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

Six people, including four children, died on Muli. One of the adults who died was in a hospital in the eastern area and was carried away by the seawater to the school in the western area of the island. Three children were washed away to the western lagoon; two were rescued and one remained missing. At the time of the tsunami, many people who were doing community work in the playground beside the lagoon were able to rescue people from the east being swept away to the west. All residents whose homes were completely destroyed managed to flee before the collapse. People swept away survived by grabbing

Photo 14. Explanation of the destroyed house and wall provided by Mr. Moosa Nasser, the island chief of Muli.

branched trees such as guava and bread fruit. Many survived by climbing trees, even small children around three years old.

Thirty houses were completely destroyed in Muli. The completely or almost completely destroyed buildings were distributed along the eastern coast of the island (cross-hatched portion of Figure 41). The school wall built three months before the tsunami collapsed (Photo 15). Eighty-eight buildings needed repair. The harbor at the western coast was also damaged (Photo 16). Most of the island area was inundated, but not the island office, mosque or two homes. At the end of August 2005, eight houses were being rebuilt, including some two-story houses.

Photo 15. Destruction of recently constructed school wall on Muli (August 2005).

Naalaafushi. An E-W profile across the island was measured in Naalaafushi (Fig. 43). The island is 150 m wide and the height is 0.6-to-1.1 m above MSL, which is relatively low compared to other islands (Fig. 44). The tsunami arrived at Naalaafushi first among the islands in Meemu Atoll. Watermarks were higher in the east, with a maximum level of 2.3 m above MSL.

Photo 16. Damaged harbor at the western coast of Muli (March 2005).

Kolhufushi. Kolhufushi, located at the southeastern rim of Meemu Atoll, is known as a fishery and for cultivation of yams. Double shallow faro-lagoons are formed between the island and deep atoll lagoon to the west of Kolhufushi (Fig. 45 left). Two villages (Northern Village and Southern Village) are located on the island. The E-W profiles across each village were measured (Fig. 45 right).

The profile across Northern Village (T1) showed a small beach ridge of 1.2 m above MSL at the eastern end, while the inhabited area of the central and western parts of the island lies at 0.5-to-0.9 m (Fig. 46-T1). Watermarks in homes were higher in the east, at 2.2 m above MSL at maximum.

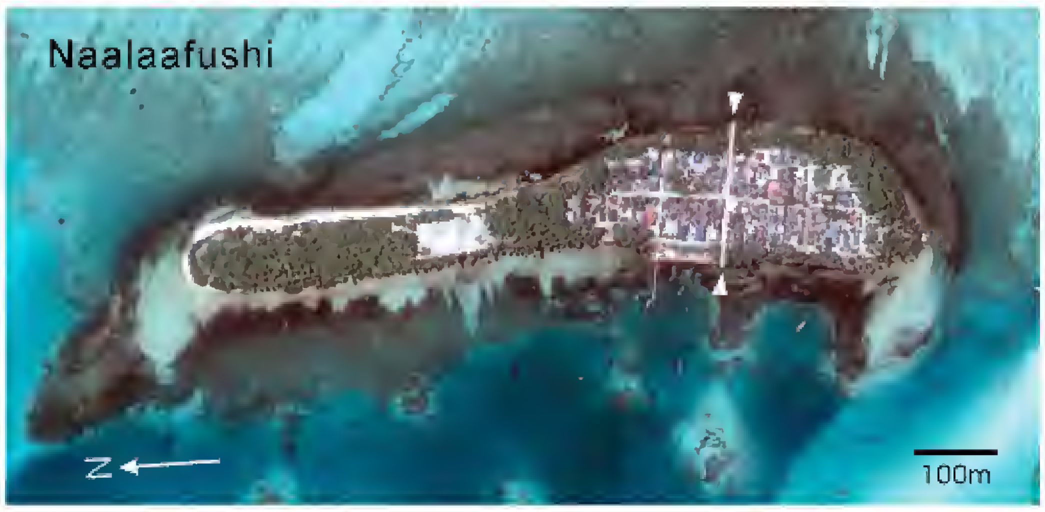

Figure 43. Location of transect at Naalaafushi, Meemu. The satellite image is provided by Google Earth.

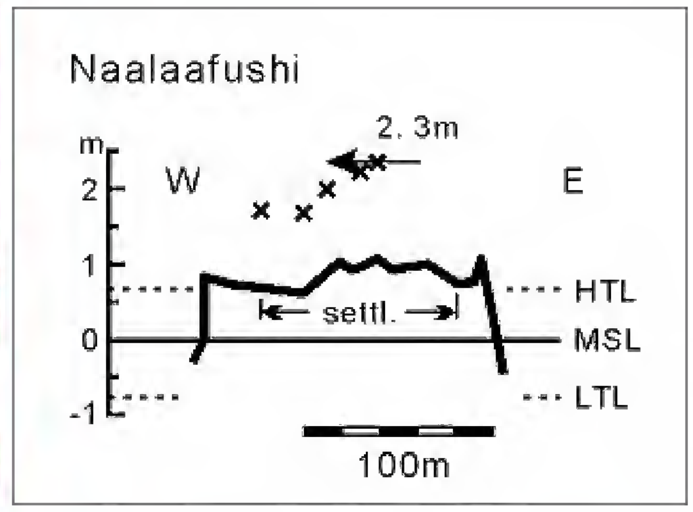

Figure 44. E-W profile of Naalaafushi (for location see Figure 43). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

The profile across Southern Village (T2) also showed a small beach ridge of 1.5 m above MSL at the eastern end (Fig. 46-T2). The profile was measured along a road that local residents paved with debris at the eastern end, although coconut forest floor also forms the ridge topography. Therefore, the beach ridge along the eastern coast is 1.3-to-1.5m above MSL. The inhabited area lies only 0.6-to-0.7 m above MSL. Seven watermarks in homes along the road were higher in the east, at 3.1 m above MSL at maximum (Photo 17).

Information regarding the tsunami on Kolhufushi was provided by an island officer, Mr. Ahmed Waheed, who also guided us around the island. A loud noise something similar to blasting continued for about 10 minutes before the tsunami arrived. According to a woman who was washing dishes on the eastern beach, the seawater bubbled like it was boiling, the sea level then dropped to expose the sandy floor of the reef flat and a large wave came from the east. The tsunami initially surged to the Southern Village, then to the Northern Village, located 0.8 km north, about two minutes later. The tsunami had not yet reached the Northern Village when a man from the Southern Village rushed by bicycle to tell the Northern Village residents. Beach erosion occurred along the southeastern coast of this island.

According to local residents, the tsunami from the east reached around 4.5 m at the eastern coast and 3.0 m at the eastern end of the inhabited area. More flood water at around 1.2 m height surged from the west (from the lagoon) five minutes after the tsunami from the east.

At the time of tsunami, the loud noise brought most people outside onto the road, causing many people to be swept away. One woman was pushed up onto a 3-m high roof with her baby and survived, indicating that the tsunami momentarily reached 3m above the road. Many people sought refuge on roofs or in trees after the tsunami. The island population before the tsunami was 1,238, and 200-to-300 people from the two villages (between a sixth and a quarter of the entire population) were swept away to the faro lagoon, west of Kolhufushi. Most of these people were pushed back to the island and survived a wave from the west five minutes after the first tsunami. Dhonis played

Figure 45. Faroes and passes around Kolhufushi, Meemu (left) and location of transects (right). The satellite image is provided by Google Earth.

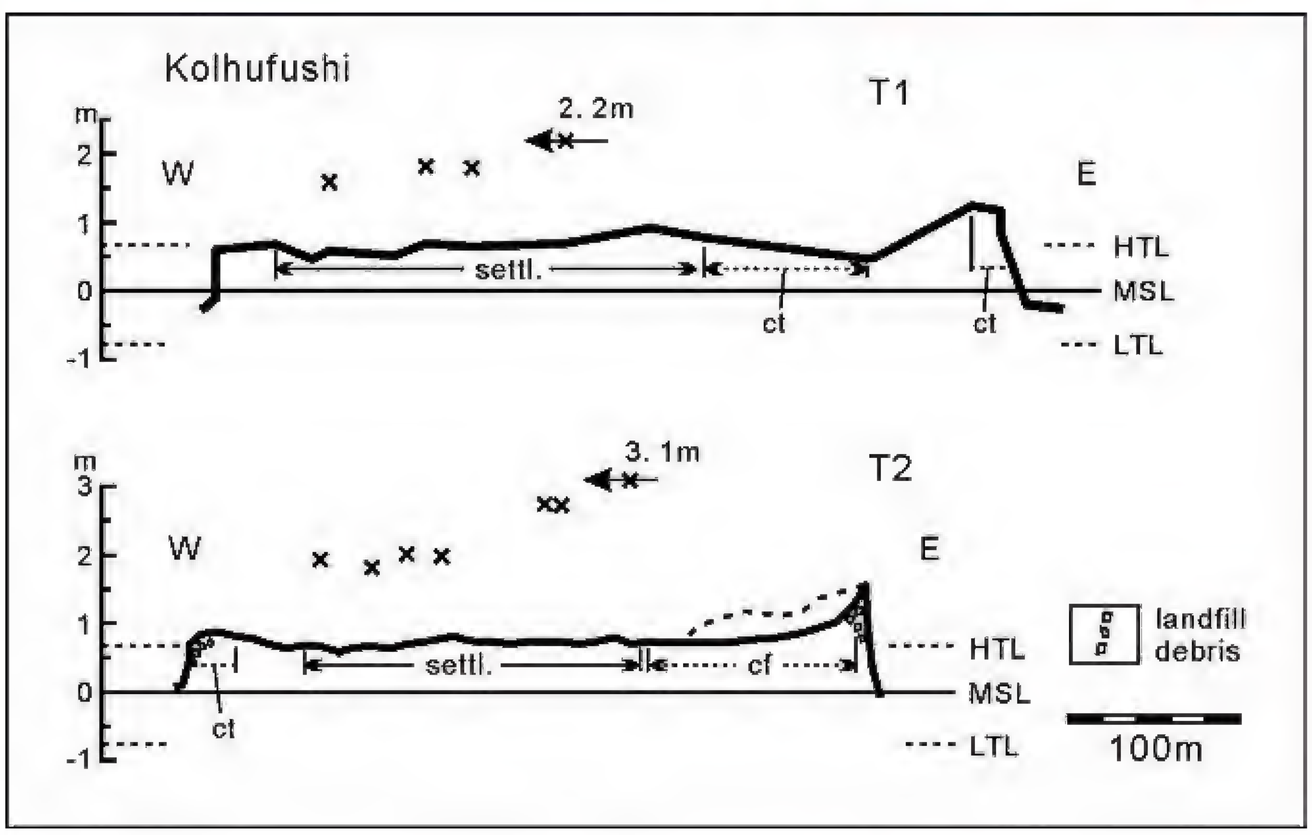

Figure 46. E-W profile of Kolhufushi (for location see Figure 45). Dashed line shows topographic relief near the transect. X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cf: coconut forest, ct: coconut trees, settl: settlement.

an active role in the rescue. Eleven died on Kolhufushi; two were girls who died in their homes and the other nine died in the lagoon. Another six were also missing in the lagoon.

Most of the island was inundated at around knee level for two weeks after the tsunami. Residents lived on dhonis for two-to-three weeks until temporary tents arrived. People lived by catching fish in seawater ponds formed by the tsunami and picking undamaged crops such as banana. All mango and breadfruit trees withered. In some areas, all trees except coconut trees were washed away. Most of the houses were in ruins in August 2005. Only four houses in the Northern Village and three in the Southern Village were suitable for habitation. Many residents were living in temporary housing built on reclaimed land at the western coast.

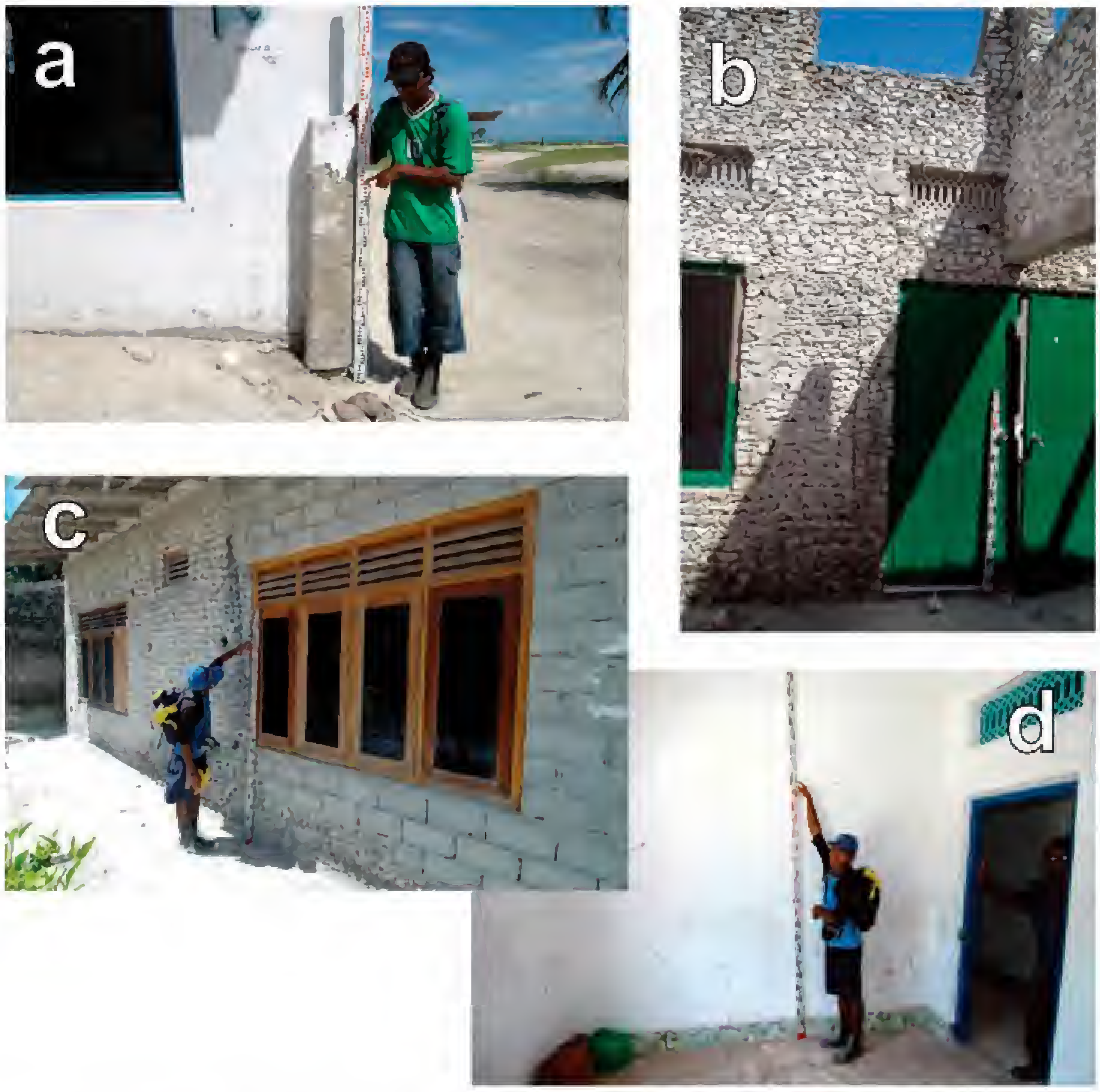

Photo 17. Watermarks on Kolhufushi (August 2005). a-d are arranged from W-E along T2 transect.

Kurali. Kurali is an uninhabited island of about 350 m by 150 m located at the southwestern rim of Meemu Atoll (Fig. 47). The maximum height of the island is 1.4 m above MSL (Fig. 48). Fresh fragments of branching corals were observed to have been deposited on the beach. There was no other observable tsunami damage to the island.

Figure 47. Location of transect at Kurali, Meemu. The satellite image is provided by Google Earth.

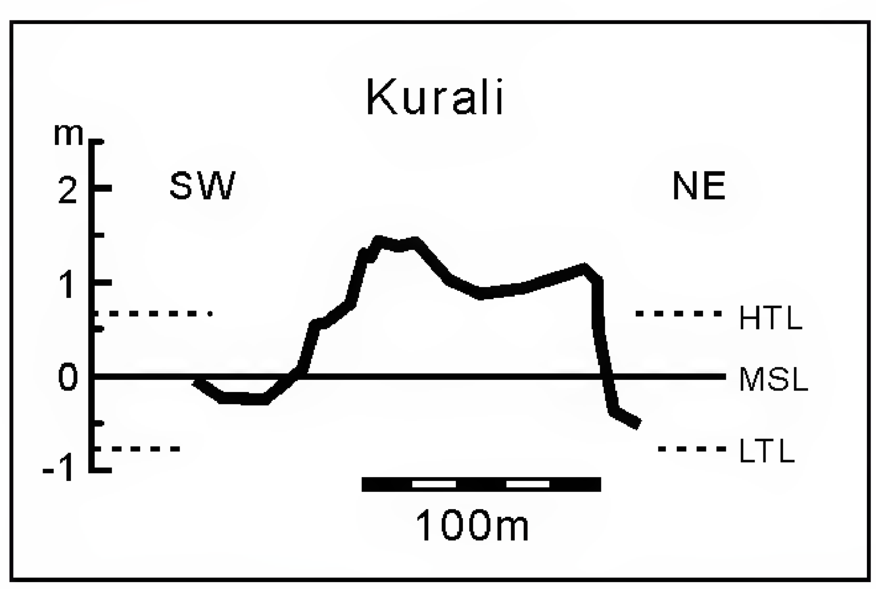

Figure 48. NE-SW profile of Kurali (for location see Figure 47). MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

Faafu

Faafu Atoll (North Nilandhe Atoll) is an atoll of 26 km in the E-W direction and 30 km in the N-S direction, located in the northwest of Meemu Atoll in the western atoll chain of the Maldives. One island, Feeali, was surveyed in Faafu Atoll.

Feeali. Two profiles in a NE-SW direction (T1) and NW-SE direction (T2) were measured at Feeali, located at the northeastern rim of Faafu Atoll (Fig. 49). Settlements cover much of the island area, with most areas lying 0.4-to-0.8 m above MSL, only the central part lies higher at 1.3 m above MSL (Fig. 50). The tsunami came from all around the island. The highest watermark observed was 0.9 m above MSL.

Figure 49. Location of transects at Feeali, Faafu. The satellite image is provided by Google Earth.

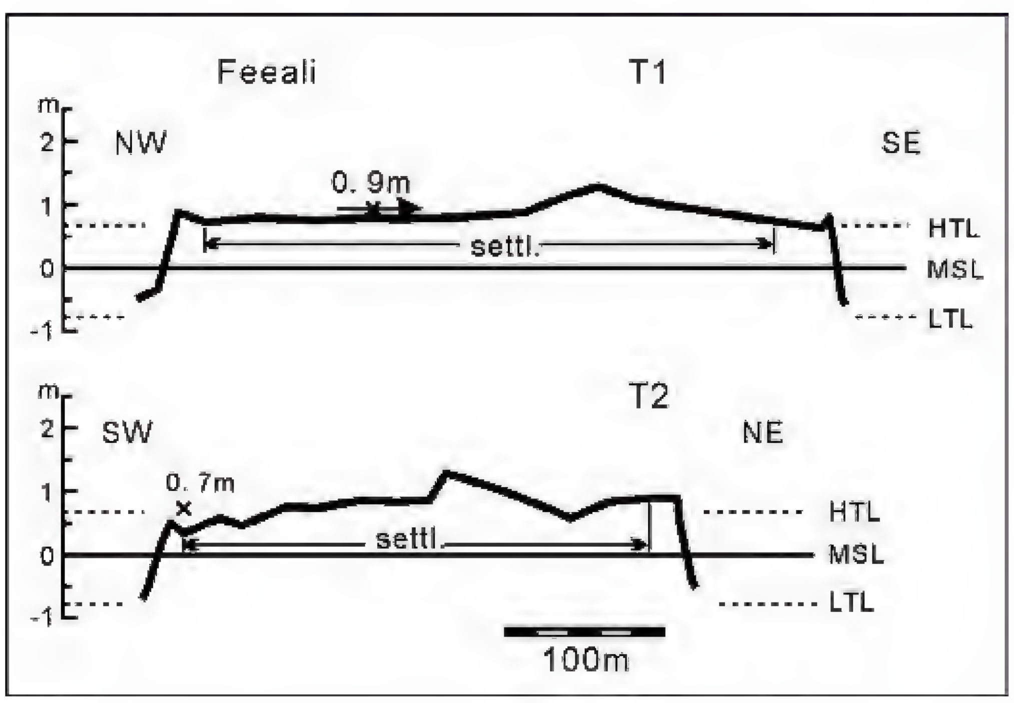

Figure 50. SE-NW and NE-SW profiles of Feeali (for location see Figure 49). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

Figure 51. Location of transects at Ribudhoo, Dhaalu. The satellite image is provided by Google Earth.

Dhaalu

Dhaal Atoll (South Nilandhe Atoll is located 6 km south of Faafu Atoll, separated by a channel. Three islands were surveyed in Dhaal Atoll.

Ribudhoo. Two topographic profiles of NW-SE and NE-SW directions were measured in Ribudhoo, situated in Dhaalu lagoon (Fig. 51). Ribdhoo is a low, flat island that has settlements at 0.9-to-1.9 m above MSL (Fig. 52). Tsunami seawater entered from all around the island. Fourteen watermarks were measured along two transects. The highest watermark was 3.4 m above MSL.

Kadimma. Kadimma is an uninhabited island 2.5 km long (NE-SW direction) and about 100 m wide, located at the southeastern rim of Dhaal Atoll. The island was separated into three pieces due to tsunami-induced erosion (Photos 18 and 19). Scouring and sedimentation caused by the tsunami were also observed along the measured profile (Fig. 53).

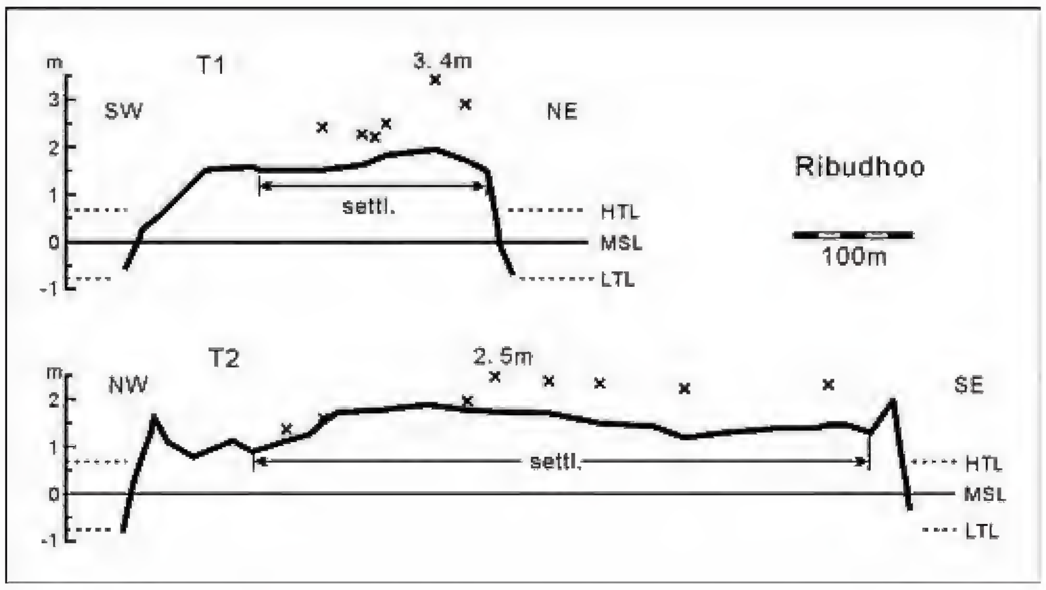

Figure 52. NE-SW and SE-NW profiles of Ribudhoo (for location see Figure 51). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

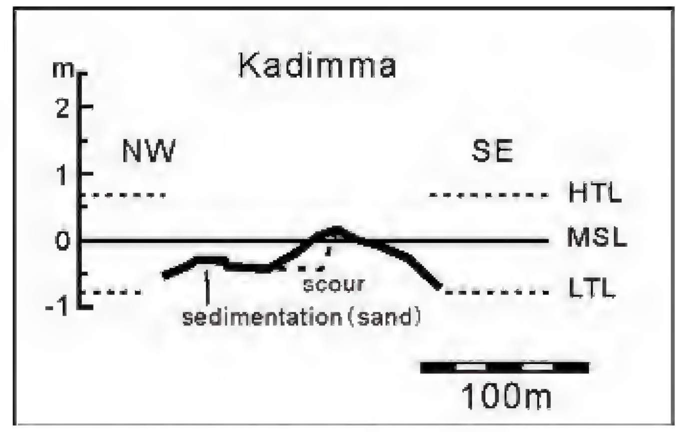

Figure 53. SE-NW profiles of Kadimma, Dhaalu. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

Photo 18. Island cut off by tsunami, Kadimma (March 2005).

Photo 19. Coral rubble below sandy sediments exposed by erosion at Kadimma (March 2005).

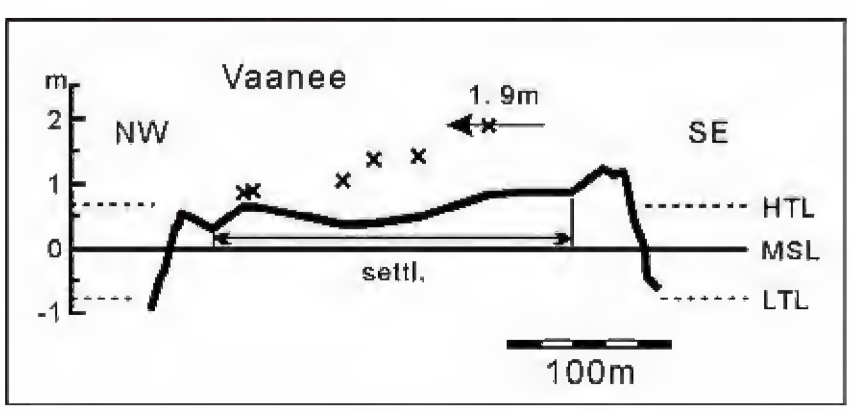

Figure 54. SE-NW profiles of Vaanee, Dhaalu. X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

Vaanee. A profile was measured in a NW-SE (313˚-133˚) direction in Vaanee, located at the southeastern rim of Dhaalu Atoll. The southeastern part of the island is slightly higher, up to 1.0-to-1.2 m above MSL. However, the inhabited area lies 0.3-to-0.9 m above MSL (Fig. 54). The highest watermark of 1.9 m above MSL was recorded in the southeastern part of the island from among six watermarks measured along the transect.

Thaa

Thaa Atoll (Kolhumadulu Atoll) is an atoll of 55 km in the E-W direction and 45 km in the N-S direction, located from 2°10' to 2°34' N, 72°53' to 3°23' E (Fig. 3-2). The atoll

chain of the Maldives forms a line in the south from Thaa Atoll. Six islands including two uninhabited islands were surveyed in Thaa Atoll.

Buruni. A profile in the NE-SW direction was measured in Buruni, located at the northern rim of Thaa Atoll (Fig. 55). The height of the island is between 1.0 and 1.5 m above MSL (Fig. 56). Reclaimed land (20 m wide) forms the southern end of the measured profile. The maximum tsunami run-up height estimated from watermarks was 1.9 m above MSL.

Olhugiri. Olhugiri is an uninhabited island located at the northeastern rim of Thaa Atoll. Two profiles in the NE-SW (20˚-200˚) and NW-SE (306˚-126˚) directions were measured on the island. The island height is between 0.6 and 1.2 m (Fig. 57). The tsunami run-up height estimated from a watermark on a palm tree was 1.6 m.

Vilufushi. Vilufushi, located at the northeastern rim of Thaa Atoll, suffered severe tsunami damage, with 17 reported dead or missing. Most buildings received damage (Photo 20). The tsunami came from the east, although waves reflected by the reef also hit from the north and south. A profile in the ENE-WSW direction was measured (Fig. 58). The entire area of the 300 m profile is the settlement area located 1.0-to-1.6 m above MSL (Fig. 59). The run-up height estimated from watermarks was 2.6 m above MSL.

Kalhufahalafushi. Kalhufahalafushi is an uninhabited island extending 6.5 km in a narrow strip from north-to-south at the eastern rim of Thaa Atoll. The island was eroded and separated into pieces by the tsunami. The height of island ranges from 1.0-to-2.0 m above MSL (Fig. 60). Beachrock was broken into pieces of about 2 m in diameter and 50-to-70 cm in thickness and piled up along the western coast (Photo 21). Erosion formed a 70 cm scarp along the western beach (Photo 22).

Madifushi. A NW-SE profile was measured in Madifushi located at the eastern rim of Thaa Atoll (Fig. 61). The height of island lies between 0.6 and 1.0 m above MSL (Fig. 62). The highest watermarks, 2.8 m above MSL at maximum, were recorded in the southeast.

Kadoodhoo. Kadoodhoo is located at the western rim of Thaa Atoll. Two channels (Kadoodhoo Kandu, Hirilandhoo Kandu) cut into the Thaa lagoon from the open ocean in the south of the island. A 520 m profile in the E-W direction was measured. The inhabited area is located between 0.7 and 1.0 m above MSL at the eastern side (lagoon-side) of the island (Fig. 63). A small ridge of 1.4 m above MSL with coastal vegetation is located at the western end of the profile. Coconut forest at the western part lies on a surface at a height of 0.7-to-1.0 m above MSL. The maximum height of a watermark of 1.4 m above MSL was recorded at the eastern end of the island.

Laamu

Laamu Atoll (Hadhdhunmathee Atoll) is an atoll of 50 km in the NE-SW direction and 28 km in the NW-SE direction, located from 1°47' to 2°08' N, 73°14' to 73°35'E (Fig. 3-2). Seven islands were surveyed among the heavily damaged islands along the eastern rim of Laamu Atoll.

Dhabidhoo. The island chief, Mr. Abdulla Saeed, recounted the tsunami events and guided us around Dhabidhoo. The tsunami arrived from the east after a loud noise was

Figure 55. Location of transects at Buruni, Thaa. The satellite image is provided by Google Earth.

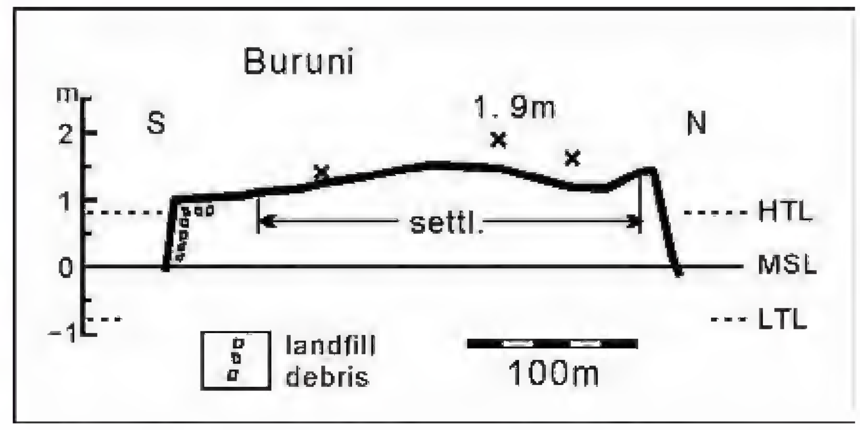

Figure 56. N-S profile of Buruni (for location see Figure 55). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

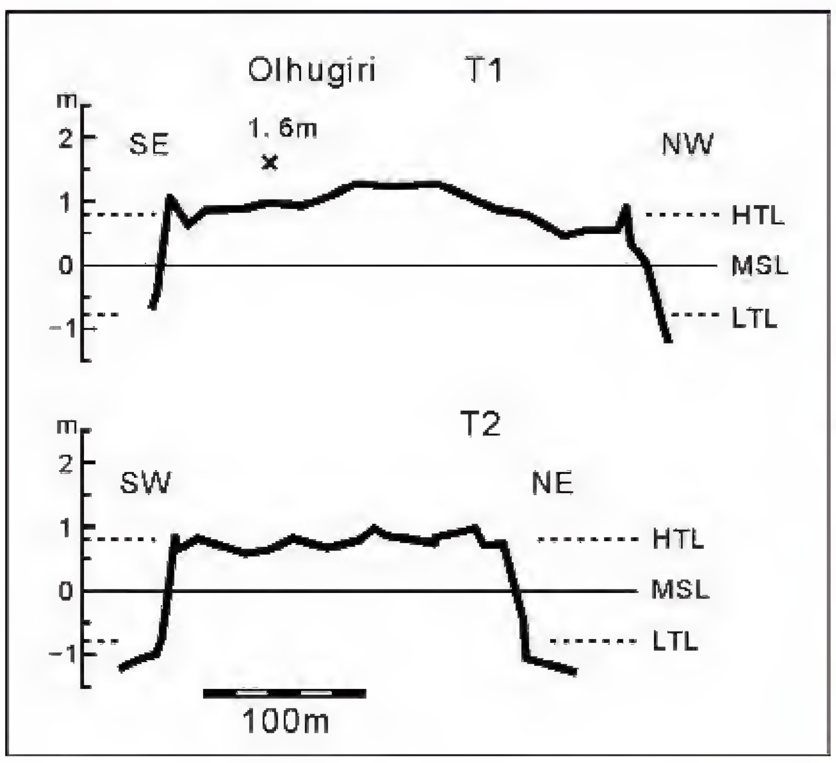

Figure 57. SE-NW and NE-SW profiles of Olhugiri, Thaa. X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

Figure 58. Location of transects at Vilufushi, Thaa. The satellite image is provided by Google Earth.

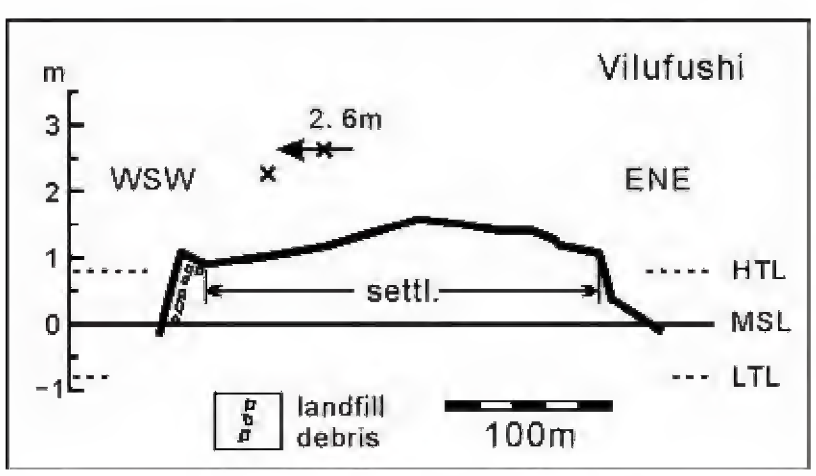

Figure 59. N-S profile of Vilufushi (for location see Figure 58). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

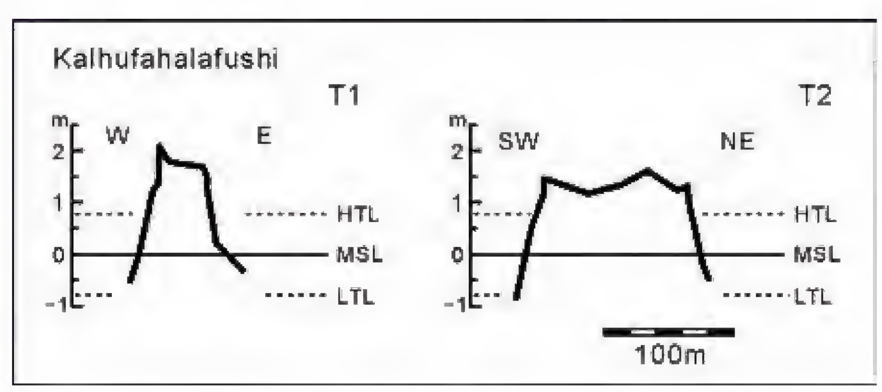

Figure 60. E-W and NE-SW profile of Kalhufahalafushi, Thaa. MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level.

Photo 20. Post-tsunami photographs of Vilufushi (March 2005). a-c: destructive damage in the settlement area; d: scouring under a house; e: dhoni run up into the village; f: harbor damage at the western coast.

Photo 21. Block of beach rocks torn off and piled up on Kalhufahalafushi (March 2005).

Photo 22. Erosion scarp on Kalhufahalafushi (March 2005).

Figure 61. Location of transects at Madifushi, Thaa. The satellite image is provided by Google Earth.

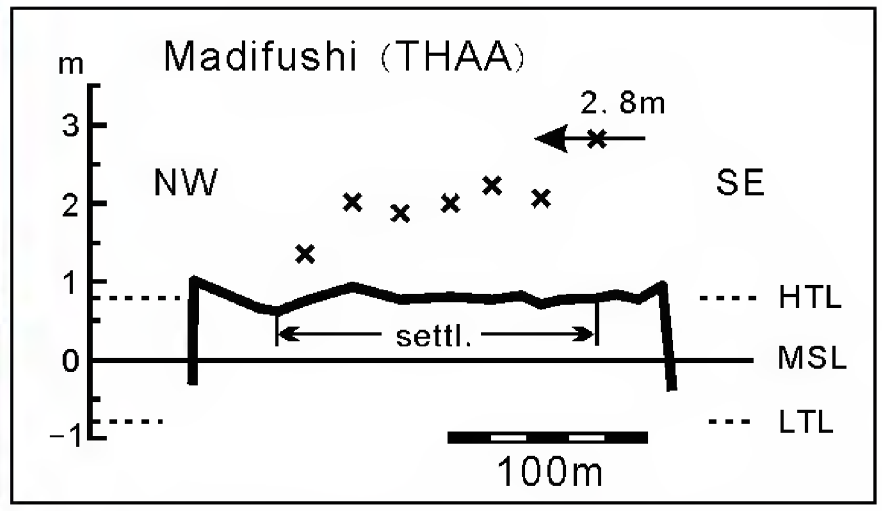

Figure 62. SE-NW profile of Madifushi (for location see Figure 61). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

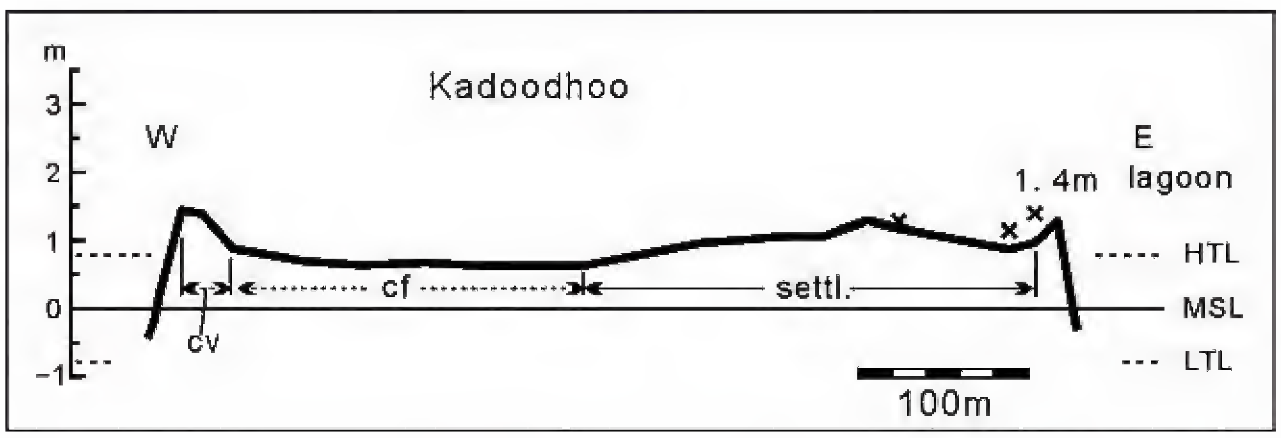

Figure 63. E-W profile of Kadoodhoo, Thaa X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cf: coconut forest, cv: coastal vegetation, settl: settlement.

heard for about 2-to-3 minutes. According to people on the eastern beach, the tsunami reached around 3.6 m. The residents ran to the football ground at the western end of the island upon hearing the loud noise and were largely protected because the ground walls held against the tsunami. After inundation, the seawater subsided after only about 2-to-3 minutes. Water reached chest height in homes near the east coast and around knee height in the island office near the west coast. Telecommunications were operational again the day after the tsunami.

One boy and one woman aged 65 died on Dhabidhoo. Twenty-nine houses were completely destroyed, especially near the eastern coast (Fig. 64, Photo 23). The collapsed houses in the western part of the island were due to sand erosion at the foundations.

The measured profile at the southern part of the village shows land is higher in the east, from 0.7-to-1.5 m above MSL (Fig. 65). Along the transect, homes were completely destroyed for 60 m from the eastern end of the inhabited area. Floor tiles were thrust up in a house named Westry situated 70 m from the eastern end of the inhabited area (Photo 24) where a watermark on the wall indicated a level of 2.8 m above MSL.

Maabaidhoo. On Maabaidhoo, a saltmarsh is located in the mid to northern part of the island and the village is in the south (Fig. 66) with a coconut forest to the eastern side of the village. Most of the inhabited area is located 1.0-to-1.7 m above MSL (Fig. 67). However, the eastern part is relatively low lying (0.8-to-0.9 m above MSL) and suffered severe damage (Photo 25).

Figure 64. Area of destruction and location of transect at Dhabidhoo, Laamu. Red areas were completely destroyed. Aerial photographs were taken in 1999 by the Maldive Government. C: cemetery, FG: football ground, I: island office, T: temporary houses.

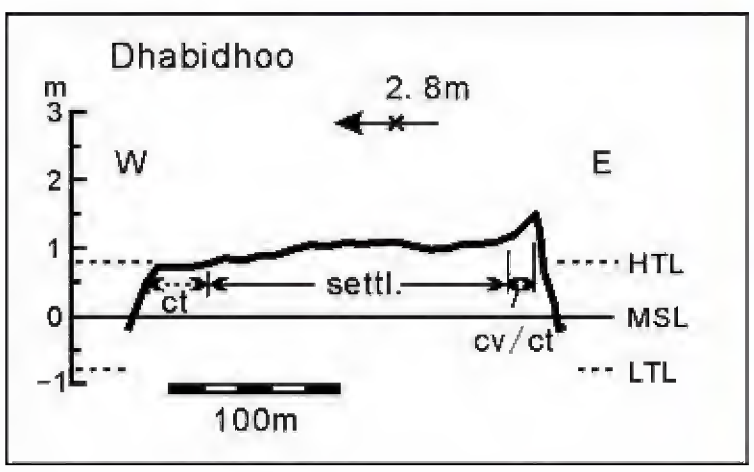

Figure 65. E-W profile of Dhabidhoo (for location see Figure 64). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, cv: coastal vegetation, settl: settlement.

Figure 66. Area of destruction and location of transect at Maabaidhoo, Laamu. Red areas were completely destroyed. Aerial photographs were taken in 1999 by the Maldive Government. H: Hospital, T: Temporary housing, WM: watermark.

Photo 23. Destroyed area near the eastern coast of Dhabidhoo (August 2005).

Photo 24. Lifted floor tiles near the eastern coast of Dhabidhoo (August 2005).

Photo 25. Destroyed area near the eastern coast of Maabaidhoo (August 2005).

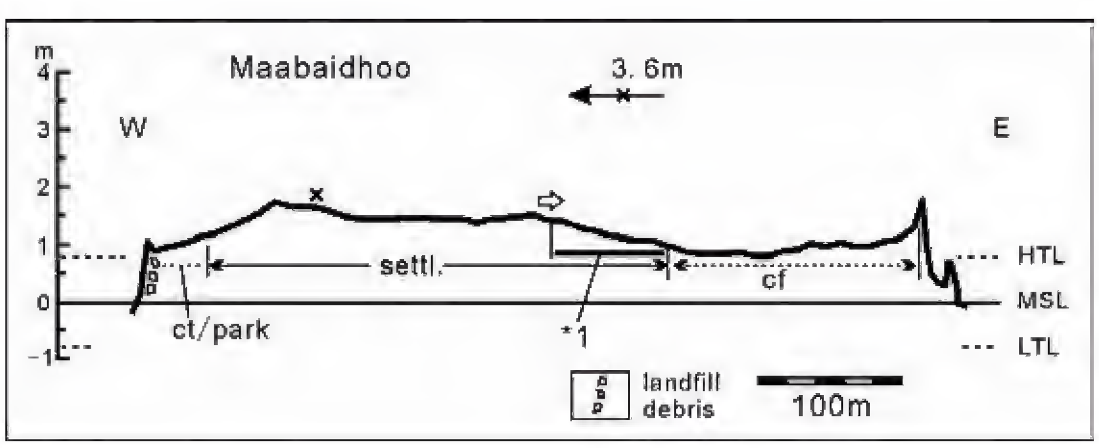

Figure 67. E-W profile of Maabaidhoo (for location see Figure 66). White arrow shows the photographic direction of Photo 25-top. *1: houses in the area completely destroyed, cf: coconut forest, ct: coconut trees, settl: settlement.

Many Photographs of the tsunami are stored in the island office. Mr. Ibrahim Fasaah, an island officer, guided us around the island and related the events on Maabaidhoo. The tsunami hit the island simultaneously from the east and northeast. Firstly, floor tiles in homes and the bottom of concrete wells were thrust up, and water rose to knee height (ca. 0.3 m) at the eastern part of the island around the coconut forest. This indicates that the water level of the first wave reached approximately 1.0-to-1.3

m above MSL. This first wave did not reach the inhabited area. A second larger wave arrived within a few seconds. Some Photographs in the island office record the first and second waves (Photo 26). This second wave reached the bottom of the coconut leaves (ca. 2-to-2.5 m above land) at the eastern coconut forest. Houses were completely destroyed 80 m from the east end at the northeastern part of the inhabited area. A watermark on a wall next to the area of destroyed homes indicated the seawater rose to 2.03 m above the road, or 3.6 m above MSL (Fig. 67). For about two hours the water remained on the island at around chest height in the eastern area and at around knee height in the western area (Photo 27). Water remained for two days on the uninhabited reclaimed land (originally saltmarsh) to the north of the village.

Fifty-six houses were completely destroyed. Our mapping (Fig. 66) showed that most of these destroyed houses were located along the eastern side of the village. No dead or missing persons were reported from the area of destruction. According to Mr. Fasaah, all residents were swept away from their houses before collapse and survived by hanging onto trees. People inside their homes came outside when the first wave came, and were returning back inside just as the second large wave came. The people in their homes could not remember how they survived. The surviving residents had a narrow escape because their homes collapsed as they were being swept away.

The major livelihood activity on Maabaidhoo is fishing. While there was not much agricultural damage to this island, human disaster occurred at the northern saltmarsh. Usually only an area manager resides in the saltmarsh. However, at the time of tsunami, a man, his two sons and nephew were collecting wood around the marsh and were swept into the lagoon. The man was rescued by dhoni, but the bodies of the three children were found later. As on other islands, dhonis moored in the harbor played an important role in rescue (Photo 28).

Kalhaidhoo. In Kalhaidhoo, the village is located beside the lagoon and coconut forest is distributed at the eastern part of the island (Fig. 68). The E-W profile shows altitudes between 1.0-to-1.1 m above MSL for the inhabited area and 0.7-to-0.8 m for the eastern coconut forest (Fig. 69).

The E-W width of the island is 450 m. A line of beach rock remains on the reef-flat 80 m off the eastern beach indicating that the island has been reduced in size by erosion. From the distribution of beach rock on the reef flat (Fig. 69), shore erosion seems to be active at the northeastern coast. According to residents, the shore was eroding before the tsunami. No beach erosion occurred due to the tsunami.

The tsunami arrived from the northeast. Many women were washing dishes along the eastern shore when it arrived. The reef flat was almost dry because of low tide and the wave surged to the island in three stages. The water initially came up from underground accompanied by the sound of bubbling, and then bubbling water came up onto the reef flat. The water level rose to knee height in the inhabited area. While the first surge was ebbing, the second bubbling occurred and the water level rose. However, the second surge did not reach the former water level. The highest wave came at the third stage. The wave set-up on the reef and island, then reached the full height of the interviewed residents (ca. 1.6 m), equal to 2.7 m above MSL. A watermark in a house along the

1st Wave

2nd Wave

Photo 26. Tsunami arrival on Maabaidhoo (photographs collected by Maabaidhoo Island Office).

Photo 27. Tsunami in the village (photographs collected by Maabaidhoo Island Office).

Photo 28. People escaped by dhonis (photograph collected by Maabaidhoo Island Office).

Figure 68. Location of transect at Kalhaidhoo, Laamu. Aerial photographs were taken in 1999 by the Maldive Government.

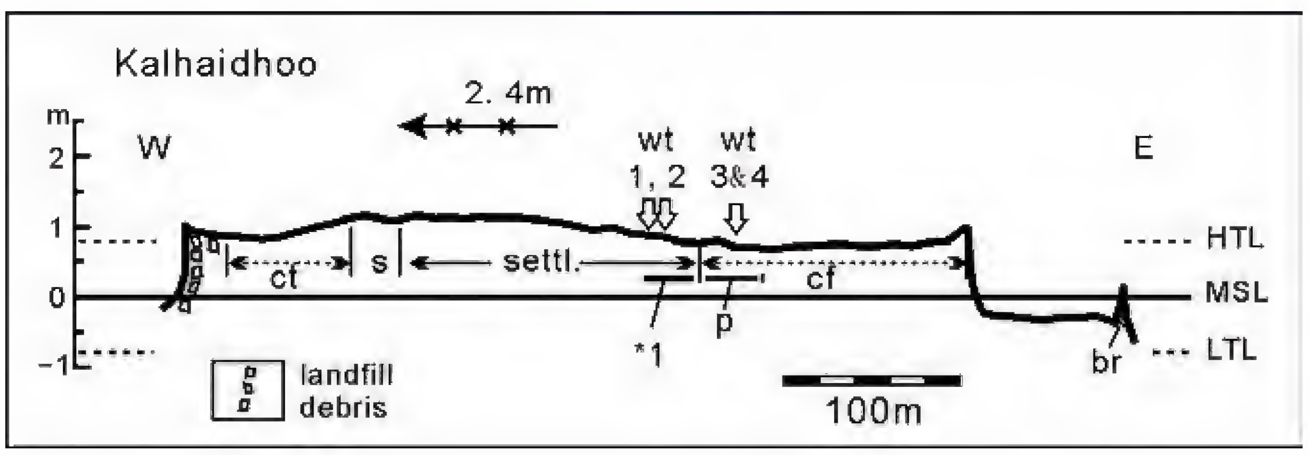

Figure 69. E-W profile of Kalhaidhoo (for location see Figure 68). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, *1: houses in the area completely destroyed, br: beach rock, cf: coconut forest, ct: coconut trees, p: power plant, s: school, settl: settlement, wt: water tank.

transect indicated a level of 2.4 m above MSL. Approximately two minutes passed between the first wave and the highest third wave.
The sea water remained on the island for about 15 minutes after the third wave.

An island officer informed us that the island population was 890 before the tsunami and 606 in August 2005. People took refuge in Gan after the tsunami. In August 2005, 122 of them remained in the industrial area there. Two were confirmed dead and one missing on Kalhaidhoo after the tsunami; one of the dead was a boy, among five children in a private preschool located at the eastern end of the island who died under a collapsed wall and the other was a woman. The missing person, the mother-in-law of a person we interviewed, was working on the farm on the uninhabited island, Kudakalhaidhoo, that serves as agricultural land for the residents and which is located north of Kalhaidhoo. Five other people were working on Kudakalhaidhoo at the time of tsunami and survived being swept away by hanging on to trees in which smaller pieces of wood had also been caught. Some residents were swept away to the lagoon from Kalhaidhoo. One woman was found hanging onto driftwood on a patch reef in the lagoon

six miles west of Kalhaidhoo three hours after the tsunami. The exact number of persons swept away is not recorded, but at least six were picked up on the eastern coast, and again dhonis played an important role in rescue.

Two of four concrete water tanks (3m in diameter, 2m in height) filled with freshwater were moved westward from a power plant at the eastern end. One was moved 35 m and the other, 45 m. The other two tanks, which remained near their original location, were lifted by the tsunami and came to rest on some trays used for mixing cement (Photo 29). Homes at the eastern side of the village were completely destroyed (Photo 30).

Photo 29. Concrete water tanks that were lifted by the tsunami came to rest on trays used for mixing cement (white arrow) on Kalhaidhoo (August 2005).

Photo 30. Destroyed houses on Kalhaidhoo (August 2005).

Baresdhoo. Baresdhoo is an uninhabited island used as a coconut plantation. The altitude is 1.0 to 1.5 m above MSL (Fig. 70). Ms. Shaheema, working for the plantation, related the events of the tsunami on Baresdhoo. She is only the person remaining on the island among the workers who were affected by the tsunami.

The tsunami came from the northeast. Flood waters from the northeast and east converged on the residential area in the southwestern part of the island. The water rose to chest height. The water reached above the window frame of 2.1 m above MSL (1.05 m above land level). More than 6,000 coconuts were swept away from the island.

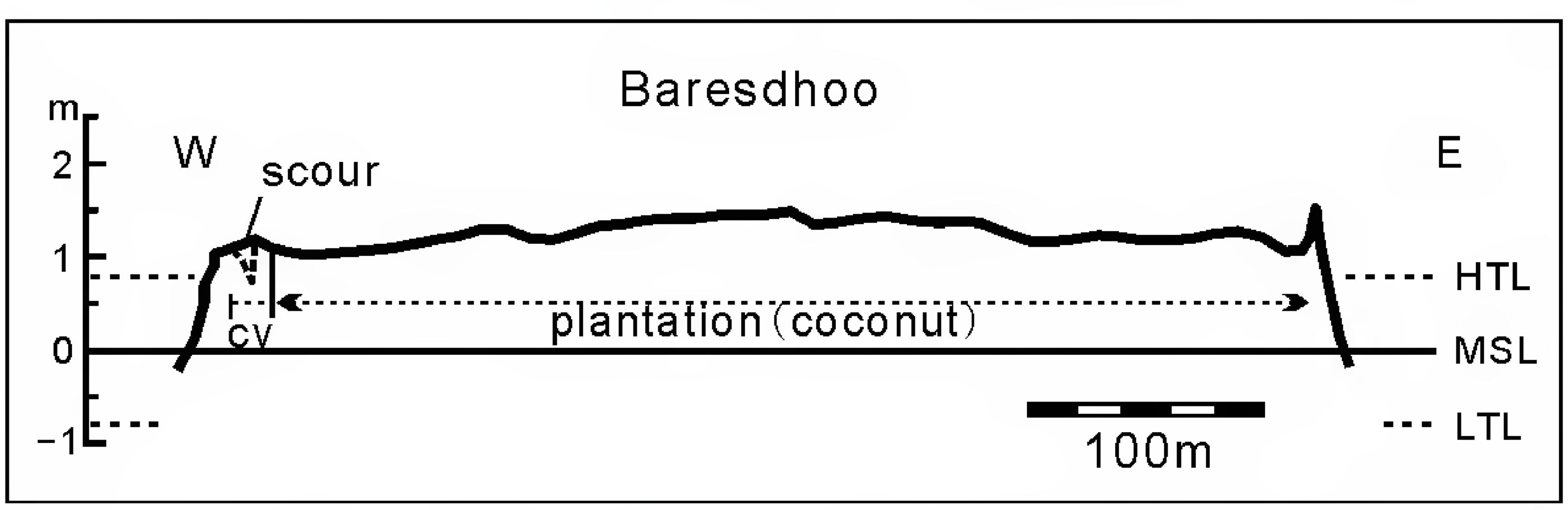

Figure 70. E-W profile of Baresdhoo, Laamu. X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, cv: coastal vegetation.

Gan. Gan is the largest island in the Maldives: 7 km N-S, a maximum width of 1.4 km E-W, and an area of 5.2 km^2 (Fig. 71). The entire island was inundated by the tsunami. According to local residents, the water level reached 1.2 m on the major N-S road. Three villages are located in Gan, from the north: Thundi, Mathimavadhoo and Mukuri Magu. Two E-W profiles were measured: 1.2 km across Mathimavadhoo and 0.33 km across Mukuri Magu (Fig. 71).

The altitude of the island is 0.8-to-1.0 m above MSL in Mathimavadhoo (Fig. 72 T1). The higher altitude at the eastern end is due to an artificial embankment. A watermark in the power plant at the easternmost part of the village is 1.4 m above MSL. No severe damage such as completely destroyed buildings occurred in this village.

Severe damage was however observed in the southern village of Mukuri Magu where the island is at its narrowest. The land lies between 1.1-to-1.5 m above MSL (Fig. 72 T2). According to local residents who were at the eastern coast, the first wave came after they observed the reef-flat water to be bubbling as though it was boiling. A second large wave came soon after the first. The wife of a local resident who we interviewed was cleaning the school at the eastern end of the village and managed to jump onto a branch of a tall tree from a 2 m wall next to the school, which was the only wall to remain standing. A part of the school building was severely damaged and debris of the school walls as large as a car was swept away to the western lagoon. However, no-one was washed into the lagoon.

An important account of the events was provided by a woman living in a house named Vruvaa west of the school. Her yard kitchen and a western wall were swept away by the tsunami. Initially, the house floor made from 30 cm^2 tiles was thrust up and about four were broken into pieces. The first wave reached around knee height (around 1.8 m above MSL).

Figure 71. Location of transects (T1 and T2) at Gan, Laamu. The satellite image (January 2, 2005) is provided by Digital Globe.

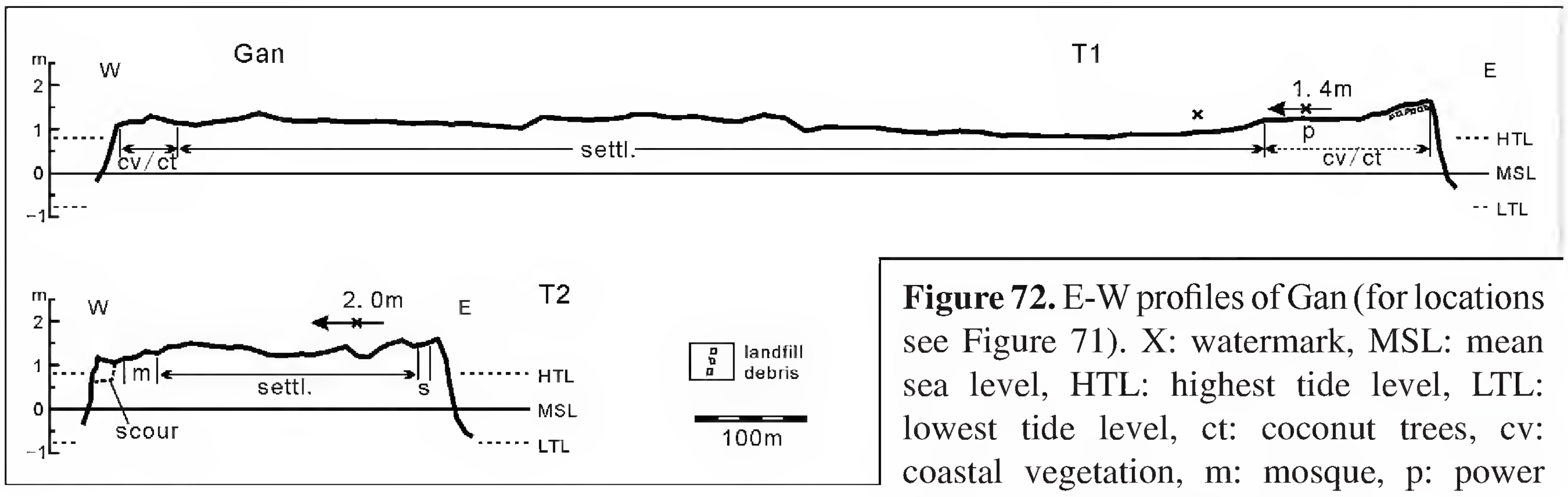

Figure 72. E-W profiles of Gan (for locations see Figure 71). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, cv: coastal vegetation, m: mosque, p: power plant, s: school, settl: settlement.

She was cooking in the annex. She extinguished the flame and ran to the main house just as the second wave came around 10 seconds after the first wave. Along the E-W road, the water reached more than 3 m above the ground and violently flowed through to the western lagoon. However, the water level was above knee height in houses beside the road. A watermark beside an oven in her house is 2.0 m above MSL, which accords well with her recollections (Photo 31).

Photo 31. Watermark near the oven at the eastern coast of Gan (August 2005).

Maandhoo. Maandhoo Island, located south of Gan, has a seafood factory and coconut plantation. Four islands (Gan, Maandhoo, Kaddhoo [the airport island] and Fonadhoo) are connected by a causeway.

In Maandhoo, the coconut plantation is situated at the eastern part of the island and a tuna factory (Horizon Fisheries Pvt. Ltd.) is located at the western part beside the lagoon. A sand embankment (relative height of 1.5-to-1.8 m) at the eastern side of the factory beside the N-S road acted as a breakwater against the attenuated tsunami by coconut trees in the plantation area. The factory had raised the floor level of new buildings by 1 m. Following the tsunami, sand embankments are being built around the site.

Fonadhoo. Two villages located in the center and south of Fonadhoo, the capital of Laamu, were surveyed (Fig. 73).

The profile across the central village (Fig. 74, T1) showed flat topography except for a small ridge of 60 m width which reaches 1.3 m above MSL covered by coconut trees and coastal vegetation at the eastern margin. The inhabited area is located from 1.1 m above MSL in the east to 1.0 m in the west. At the eastern side of the inhabited area houses collapsed due to the tsunami (Photo 32). A watermark in an easternmost house was 2.9 m above MSL (Photo 33). Another watermark 100 m west of this was 2.1 m above MSL.

The profile across the southern village (Fig. 74, T2) showed the eastern beach

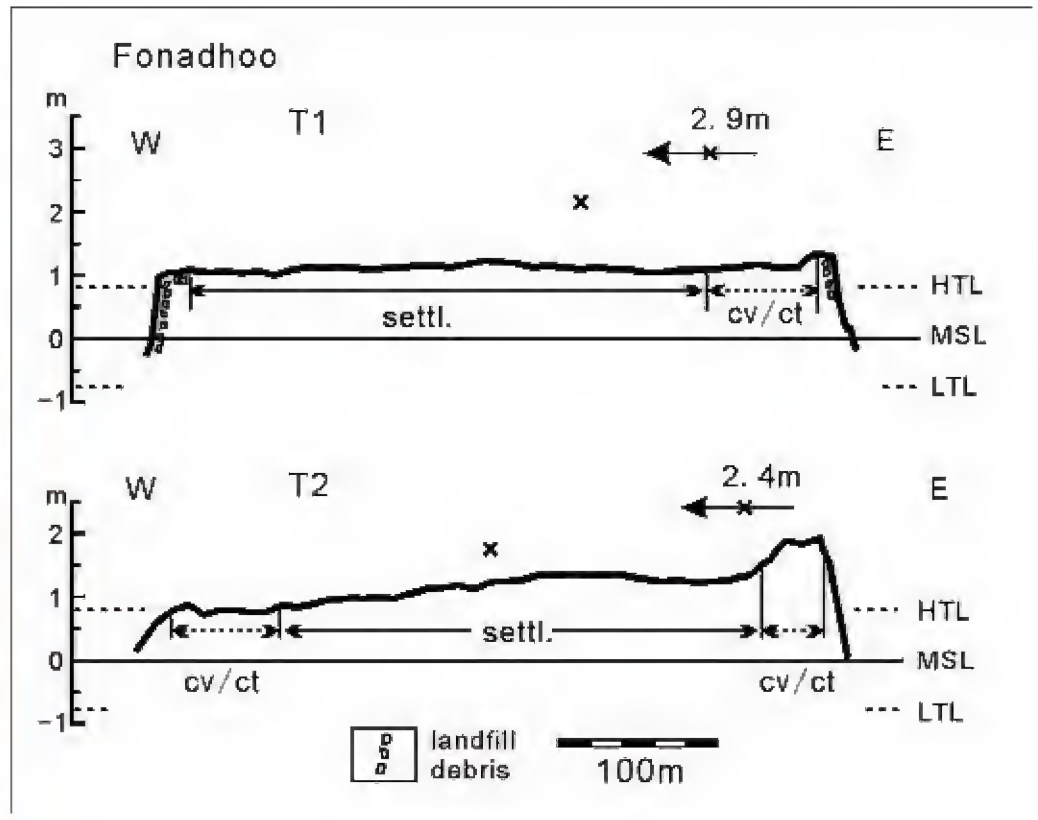

Figure 74. E-W profiles of Fonadhoo (for locations see Figure 73). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, ct: coconut trees, cv: coastal vegetation, settl: settlement.

ridge of 40 m width reaches 1.9 m above MSL, with lower altitude in the west. The inhabited area lies between 1.4 and 0.9 m above MSL. The altitude of the western side of the island is around 0.6 or 0.7 m above MSL, which is lower than the highest tide level observed from Gan over the past 15 years (81.1 cm above MSL). Watermarks were 2.4 m above MSL at the power plant located at the easternmost part of the island and 1.7 m above MSL in a telephone booth in the center of the island (Photo 34). A scouring ditch already filled by locals was observed around the power plant at the eastern coast.

Watermarks became lower in the west in both transects; those in the southern transect (T2) were lower than in the central transects (T1) by around 0.5 m. This may be related to the development of the beach ridge.

According to local residents at the eastern coast during the tsunami, after two small waves, the sea water rose suddenly to form a wall at the reef edge and surged. Presumably this was due to the steep fore reef topography as well as the narrow reef flat, where the reef edge is located close to the shore. The maximum run up height was reported to be 3 m above the land level, which is more than 4 m above MSL. No-one was washed away to the lagoon, but instead were caught in trees or against walls and survived. According to an officer in the island office, the water level quickly decreased on this island, which could be why so many people who were swept away survived.

Photo 32. Destroyed house at the eastern end of the transect T1 on Fonadhoo (August 2005).

Photo 33. Watermark in a house in the eastern area of transect T1 on Fonadhoo (August 2005).

Photo 34. Watermark on a telephone box, central part of transect T2, Fonadhoo (August 2005).

TSUNAMI EVENTS: BASED ON OBSERVATIONS OF THE MALDIVES

Tsunami Arrival Time

Tsunami arrival time reported by the island offices in Haa Alifu, Haa Dhaalu and Noonu, Raa in the northern atolls and Kaafu in the central Maldives varied from 9:00-to-9:55 local time on December 26 (Table 1, Fig. 75). In some case, later arrival times were reported from the eastern islands. In the northern atolls, many villages are located beside the lagoon where the arrival of flood water from the lagoon seems to have been recorded as the tsunami arrival time. The reported arrival time at the eastern islands in the northern atolls conformed to the highest tide (9:40) recorded at the tide gauge in Hanimaadhoo.

The arrival times from the southern atolls were not reported by the island offices because communications had ceased with Malé after the tsunami. However, in Meemu Atoll, for example, the tsunami surged to Naalaafushi earlier than to other islands so information and warnings were passed on to all other islands in Meemu via Muli, the atoll capital. This tells us that the tsunami arrival time also varied in the southern atoll.

Moreover, in Kolhufushi in Meemu Atoll, the tsunami surged to Southern Village initially, then to Northern Village located 0.8 km to the north about two minutes later. The arrival time therefore also varied within an island.

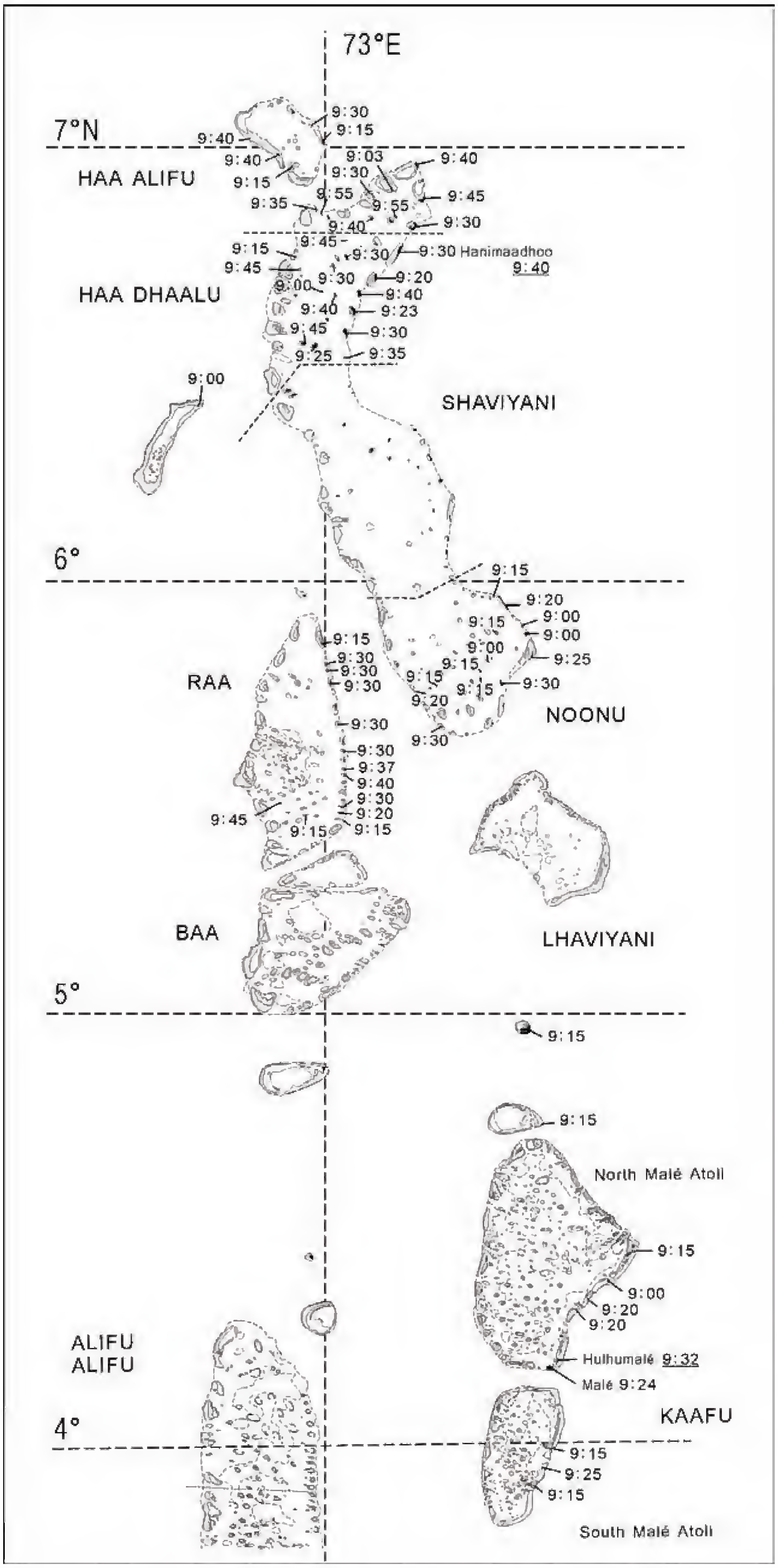

Figure 75. Tsunami arrival time in the northern atolls.

Forerunning Phenomena

In the case of the 2004 Indian Ocean Tsunami, the incoming wave arrived first in an area west of the tsunami source area, whereas the tsunami arrived after a drawdown event along the western coast of Sumatra and Thailand. Therefore, it is generally understood that the tsunami arrived without any forerunning phenomena in the Maldives. However, according to the results of our interviews in the southern Maldives, many eyewitnesses observed forerunning phenomena.

On Muli, located on the eastern rim of Meemu Atoll, loud noises and bubbling reef-flat water at the eastern coast started two minutes prior to the tsunami. This was followed by a small wave rushing in from the east that reached waist height on the island. One minute later, two large waves reaching 2.4 m on the island rushed in from the east. The forerunning phenomena thus started three minutes before the maximum surge in Muli. On Mulah, located in a channel that opens at the eastern rim of Meemu Atoll, local residents heard loud noises two-to-four minutes before the tsunami. On Kolhufushi in Meemu Atoll, locals heard loud noises similar to blasting around 10 minutes before the tsunami surge. At the eastern coast of Kolhufushi, before the maximum tsunami surge, seawater bubbled and the sea level then dropped to expose the sandy floor of the reef flat.

On Dhabidhoo in Laamu Atoll, the tsunami arrived after locals heard loud noises for two-to-three minutes. On Maabaidhoo in Laamu Atoll, floor tiles of houses and the bottom of concrete wells were thrust up with the first wave of 1.0-to-1.3 m above MSL, a wave which did not reach the inhabited area. The largest tsunami wave arrived a few seconds after the first wave. The same thrusting up of floor tiles was reported on other islands. The marked rise in ground water level seems to have occurred with the first tsunami surge due to the porous subsurface (geological) structure of the reefs and islands in the Maldives.

On Kalhaidhoo in Laamu Atoll, two small waves arrived in the two minutes preceding the maximum tsunami surge, bringing bubbling water from underground up to the island and reef flat. In Mukuri Magu on southern Gan in Laamu, bubbling reef flat water was followed by the first small wave and then the maximum surge of the tsunami. The floor tiles of houses in the eastern inhabited area were also thrust up and broken when the first small wave reached around knee height on the island. The second wave, the maximum tsunami surge, arrived around 10 minutes later. On Fonadhoo in Laamu Atoll, the maximum tsunami surge arrived like a “wall” after two small waves.

The phenomenon of the reef flat water bubbling, as though it were boiling, was reported by many islands on the eastern atoll rims, and is probably due to air in the internal cavities of coral reefs being pushed out at the low tide by the abrupt rise in inter-rock pressure caused by the tsunami surge.

Maximum Instantaneous Run-up Height of Tsunami Based on Resident Accounts

In addition to the measurements we took, we recorded many first-hand accounts of run-up heights from local residents. This evidence was typically based on standing height or palm tree height. Many such accounts agreed with observed watermarks and other

physical evidence. Moreover, maximum instantaneous run-up heights were estimated from such verbal evidence and some accounts were confirmed by the physical evidence available.

In the southern village of Kolhufushi, the highest watermark was observed at 3.1 m, but verbal evidence tells us that the maximum run-up reached 3.7 m above MSL (3.0 m above the road). Many people sought shelter on roofs or in trees after tsunami, including the woman and her baby pushed up onto a 3-m high roof. On the eastern beach of Kolhufushi, we heard accounts that the tsunami surge was around 4.5 m, which is higher than that in the inhabited area.

On Dhabidhoo in Laamu Atoll, locals related that the maximum surge reached 3.6 m at the eastern coast whereas the observed highest watermark was 2.8 m above MSL. The maximum instantaneous run-up height estimated from local eyewitness accounts was 2.7 m above MSL, which is 0.3 m higher than the highest watermark we measured.

A higher run-up with stronger current also occurred in certain areas of villages, and depended on the distribution of walls and houses against the tsunami direction. In Mukuri Magu, on southern Gan in Laamu Atoll, the water reached more than 3 m above the ground and violently flowed through to the western lagoon along an E-W road. However, the water level was only just above knee height in homes beside the road. The tsunami from the east was concentrated onto the E-W road to flow through to the lagoon.

In addition, we gathered accounts in the eastern islands of the southern atolls of, for example, "a baby sitting on a branch of a tall tree after the tsunami" and "a woman who was lifted up by tsunami to catch hold near the top of a palm tree standing to the west of where she originally stood". Such verbal evidence suggests that the maximum instantaneous run-up height was higher by at least 0.3 m and even more than 1 m in some places than the run-up heights observed from watermarks. The local effect of the tsunami set-up was estimated to reach +2.5 m due to the distribution of buildings.

TSUNAMI DISASTER IN RELATION TO THE GEOMORPHOLOGY OF REEFS AND ISLANDS

The discontinuous atoll rim consisting of many faroes is the characteristic reef topography of the northern Maldives, while rather continuous rims are characteristic of the southern atolls. Cay islands of larger area and higher altitude are distributed in the northern atolls. Many of the larger islands have zonal distribution of mature vegetation such as a coastal vegetation zone and coconut forest zone. The frequency of cyclones and the influence of the monsoon, which is greater in the northern Maldives, may contribute to the formation of mature islands. These topographic features may contribute to the differences seen in tsunami behavior in the atolls and the scale of the disaster on the islands. The following tsunami events are presumed for the northern, middle and southern Maldives.

Northern Atolls

It seems that the tsunami from the east easily entered the lagoon through the discontinuous atoll rim in the northern Maldives, possibly contributing to the avoidance of a large-scale disaster on the islands at the eastern atoll rim. A large disaster did, however, occur on some of the islands at the western atoll rim.

Islands at the eastern atoll rim have beach ridges at heights of around 2-to-3 m above MSL on the eastern side. In our research, sediment transportation from the beach ridge inland was observed on Baarah, Haa Alifu Atoll, indicating that the tsunami was interrupted by the eastern beach ridges, which in turn contributed to human disaster reduction.

A tsunami run-up height of around 1.8 m above MSL was observed from watermarks in the northern Maldives. These data were in good agreement with tide gauge data from Hanimaadhoo. In the northern atolls, inundation occurred from flood water entering from the lagoons, where the lagoon floors are relatively shallow at 30-to-40 m deep. The lagoon water level was likely set-up by the entering tsunami, a phenomenon that may be referred to as “lagoon set-up”. The altitude of villages varied from island to island; although the difference ranges from only 10 to a few 10’s of centimeters, this was the reason behind inundation or not.

Central Atolls

Beach ridges have not developed on the eastern islands in the North and South Malé Atolls or Vaavu Atoll. The altitude of these islands is low, at around 1 m above MSL. These islands were affected severely by the tsunami from the east, and were then hit by flood water from the western lagoon, causing inundation and collapse of walls. The time lags between the tsunami from the east and the flood water from the lagoon were 30 minutes for Diffushi in the North Malé Atoll, 15 minutes for the islands in the South Malé Atoll, and 4 minutes in Vaavu Atoll. The depth of the lagoon floors lies around 40-to-70 m deep in the central atolls, which is deeper than the lagoon floors of the northern atolls. The atoll rims are interrupted by many channels in the central atolls, but are more continuous than those in the northern atolls. The tsunami seems to have entered the lagoons in the central atolls to cause “lagoon set-up”.

On Diffushi in the North Malé Atoll, the tsunami height from the east was 1.5 m above MSL which concurs with the tide gauge data of 1.42 m above MSL recorded at Hulhumalé. The timing of the flood water from the lagoon (30 minutes after the tsunami) corresponds to the second surge recorded by the tide gauge. The second surge, which reflected and entered the lagoon, might have pushed up the lagoon water level which was already set up. The height of the flood water from the lagoon at Diffushi was 1.8 m above MSL which was higher than the tsunami from the east.

On Maafushi and Guraidhoo, South Malé Atoll, flood water from the lagoon was 1.4-to-1.6 m above MSL, which was lower than the tsunami from the east (2.4-to-2.5 m above MSL). The timing of the flood water from the lagoon was 15 minutes after the tsunami from the east, which corresponds to the first low peak after the tsunami recorded

by the tide gauge at Hulhumalé. The flood water from the lagoon in the South Malé Atoll, which was lower than the first tsunami from the east, is assumed to have been caused by backwash from the lagoon to the open ocean.

Many channels cut the atoll rim in Vaavu Atoll and this atoll rim topography may have contributed to disaster reduction because the tsunami easily passed through the atoll.

Southern Atolls

The islands in the southern atolls are typically low lying and flat, at an altitude around 1 m above MSL. Large disasters occurred on the eastern islands of the eastern atolls, such as Meemu, Thaa and Laamu. Catastrophic damage occurred on the eastern side of the islands where the tsunami run up height reached 3.6 m above MSL at maximum. In contrast, there was less damage on the lagoon side of the eastern islands and on the islands at the western atoll rims. No flood water from the lagoon was reported in these atolls except on Kolhufushi in Meemu.

On Kolhufushi, the flood water from the lagoon arrived only 5 minutes after the tsunami from the east. According to the submarine topography of the atoll, it seems that the tsunami reflected to the south of the atoll to enter the lagoon through the Karuli Kandu channel which opens southwest of Kolhufushi (see Figure 45 left). This may have caused the surge on Kolhufushi from the lagoon.

Flood water surged from all around Ribdhoo Island in Dhaalu Atoll in the western atoll chain of the southern Maldives. Lagoon set up is assumed to have occurred in Dhaalu Atoll as the atoll rim is discontinuous.

Tsunami run-up heights observed in this study are summarized in Table 2, and the regional differences of these run-up heights are shown in Figure 76. The higher run-up heights were observed on the eastern islands of the southern atolls. These data agree with the distribution of disaster status presented in Table 1 and Figure 2, and also coincides with the run-up heights observed by Fujima et al. (2005, 2006).

Catastrophic damage and high run-up levels occurred on the eastern islands in atolls with a continuous atoll rim in the southern Maldives. The tsunami hit the continuous atoll edge and surged to the islands on the rim. However, because the lagoon water level was not set-up significantly, there was no floodwater from the lagoon in atolls with a continuous rim. Compared to the catastrophic damage seen on the eastern islands, damage at the western atoll rims and in the lagoons was relatively small. The continuous eastern atoll rim and its islands acted as a breakwater against the tsunami from the east.

Less damage was reported from the far south of the Maldives in Gaafu Atoll (Huvadhoo Atoll), consisting of Gaafu Alifu and Gaafu Dhaalu administrative atolls and Gnaviyani (Foammulah) and Seenu Atoll (Addu Atoll), as shown in Figure 3. Two major E-W channels of around 2,000 m depth cut across the atoll chain in the far south Maldives: the One and Half Degree Channel of 100 km width and the Equatorial Channel of 85 km width. The sparsely distributed atolls and deep channels may have flowed the tsunami to the west and reduced the tsunami's impact on the far south atolls.

On the other hand, in atolls where the rims consist of numerous faroes and are interrupted by many channels, the tsunami entered the lagoons through these channels.

Table 2. Tsunami run-up height surveyed in this research

ATOLL		First Wave		Second Wave	
Map No. 1)	Island	Run-Up Height 2)	Direction	Run-Up Height 2)	Direction
HAA ALIFU (North Thiladhunmathee Atoll)					
HA08	Maarandhoo	N/A			
HA11	Vashafaru	1.8	S		
HA12	Kelaa	N/A			
HA13	Filladhoo	1.9	W		
HA14	Baarah		N	1.8	W
HAA DHAALU (South Thiladhunmathee Atoll)					
HD01	Hanimaadhoo	N/A			
HD02	Nolhivaranfaru	1.4	W		
HD03	Nolhivaramu	N/A			
HD08	Finey	N/A			
RAA (North Maalhosmadulu Atoll)					
U	Ifuru	N/A			
U	Ugulu	N/A			
R13	Meedhoo	N/A			
R15	Kandholhudhoo	2.7	?		
KAAFU (Malé Atoll)					
K03	Dhiffushi	1.5	E	1.8	W
K08	Maafushi	2.5	E	1.4	W
K09	Guraidhoo	2.4	E	1.6	W
VAAVU (Felidhe Atoll)					
V02	Thinadhoo	ca.2.4	SWS		
MEEMU (Mulaku Atoll)					
M02	Maduvvari	1.6	NE		
M03	Raiymandhoo	2.3	E		
M04	Madifushi	2.2	E		
U	Uthuruboduveli	1.5	E?		
M05	Veyvah	1.7	E	1.7	W
M06	Mulah	N/A			
M07	Muli	2.6	E		
M08	Naalaafushi	2.3	E		
M09	Kolhufushi	3.1	E		
U	Kurali	N/A			
FAAFU (North Nilandhe Atoll)					
F01	Fieeali	0.9	NW		
DHAALU (South Nilandhe Atoll)					
U	Kadimma	N/A			
D04	Vaanee	1.9	SE		
D06	Ribudhoo	3.4	All Direction		
THAA (Kolhumadulu Atoll)					
T01	Buruni	1.9	?		
U	Olhugiri	1.6	?		
T02	Vilufushi	2.6	ENE		
U	Kalhufahalafushi	N/A			
T03	Madifushi	2.8	SE		
T11	Kadoodhoo	1.4	E		
LAAMU (Hadhdhunmathee Atoll)					
L02	Dhabidhoo	2.8	E		
L03	Maabaidhoo	3.6	E		
L05	Kalhaidhoo	2.4	E		
U	Baresdhoo	2.1+	E		
L06	Gan	2	E		
L08	Fonadhoo	2.9	E		

1) Map number of Fig. 3. U: uninhabited island (not shown in Fig. 3)
2) m above MSL

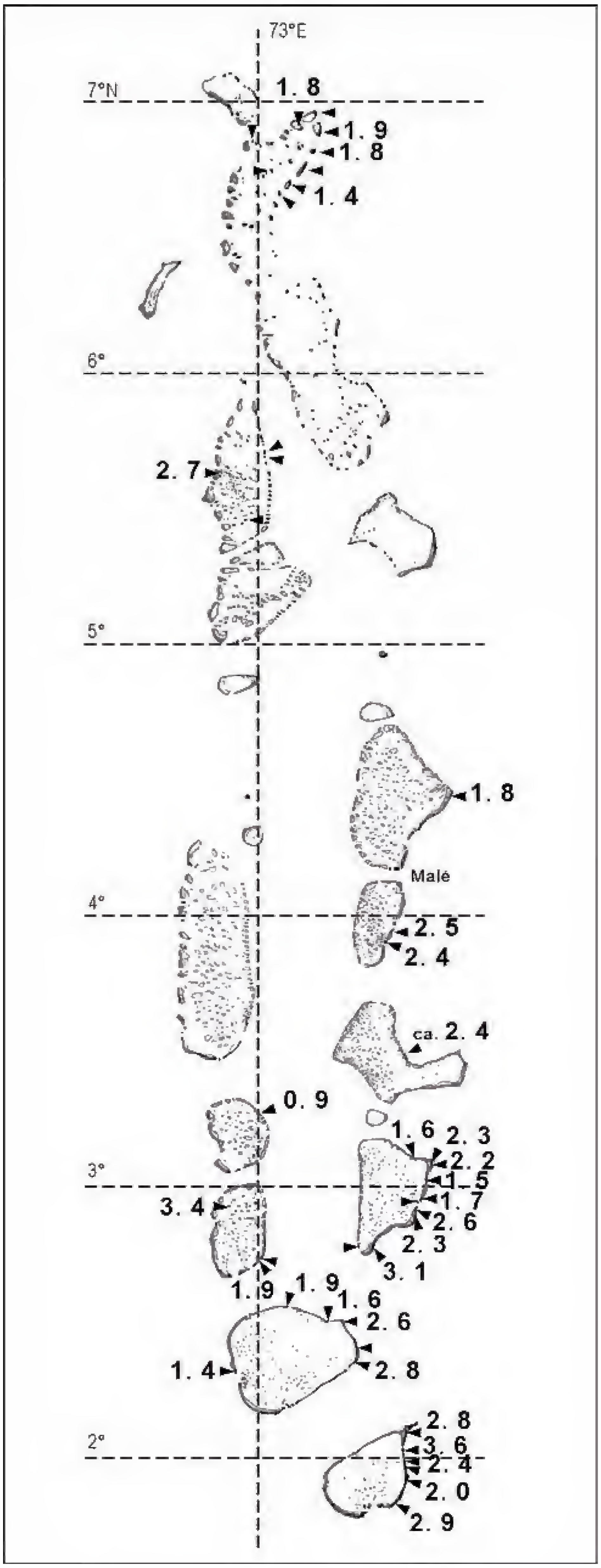

Figure 76. Tsunami run-up heights from watermarks observed in this study.

This atoll type is typical of the northern Maldives where less damage was observed on islands at the eastern atoll rim. In addition, beach ridges developed on the eastern side of these islands acted as breakwaters against the tsunami from the east. However, low lying islands on the western atoll rim and on the lagoonal patch reefs were seriously inundated. In this type of atoll, the lagoon water level seems to have been set-up by the tsunami entering the lagoon which was followed by backwash to the open ocean through the channels. This backwash might have caused the flood water from the lagoon that inundated the lagoon-side villages on islands at the eastern atoll rim. In the northern Maldives, the typical atoll topography of opening rims and large higher-lying islands with clear geomorphological zonation developed under a high-energy environment showed less tsunami-induced damage (Fig. 77).

It is noteworthy that remarkable topographic change was not observed on most of the atoll islands but instead on long and narrow uninhabited islands at the eastern atoll rims in the southern Maldives. These findings agree with the observations by Kench et al.(2006, 2007) on uninhabited islands in Baa Atoll (South Maalhosmadulu Atoll). Kench et al. (2007) report sand sheet deposit up to 0.3 m thick by unidirectional tsunami flow at the southeastern beach of Milaidhoo, an inhabited island in Baa Atoll. The deformation of coastline by transported sediment, such as movement of sand spit,

was also recognized by Gischler and Kikinger (2007) and in our research. However, extensive tsunami deposits were not observed on the 43 islands we surveyed nor have been reported from other islands in Maldives. Surprisingly, the surface sediment of these islands, which consists of sand with small amounts of organic matter, was not altered by the tsunami. Only scouring occurred on part of the coastline. Extensive reef research by AusAID (2005) confirmed that the damage to living corals was also minor throughout the Maldives. The geological-geomorphological system of atolls and islands and sublittoral ecosystem remained intact after the tsunami, although the tsunami caused serious loss of life and damage to buildings and vegetation.

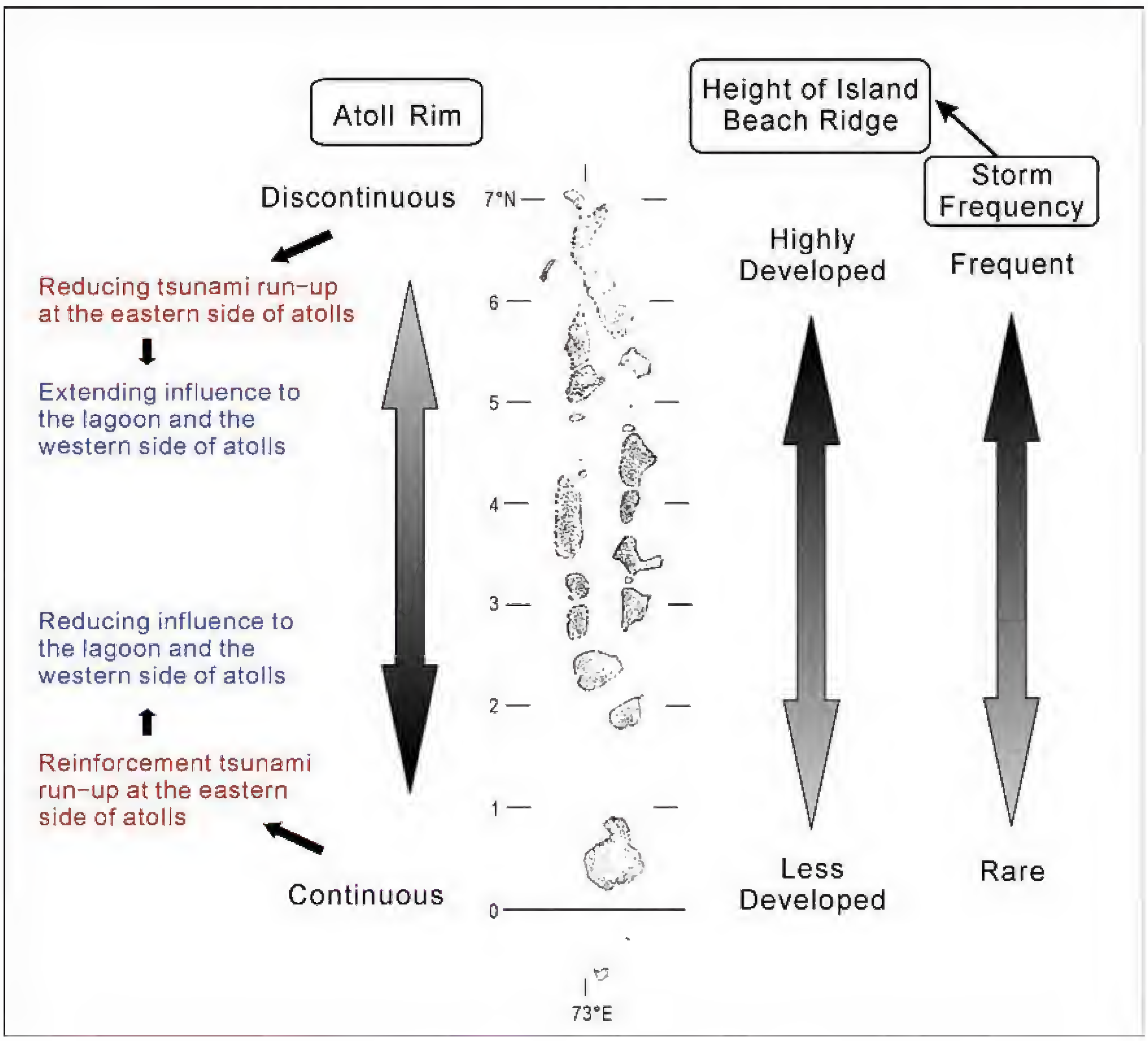

Figure 77. Geomorphological effects of the tsunami on the atoll-island system in the Maldives.

FUTURE DISASTER PREVENTION EFFORTS IN ATOLL NATIONS

The Republic of Maldives is an atoll nation of land developed on atoll reefs. The geologic and geomorphologic nature of the country differs from the other nations stricken by the 2004 Indian Ocean tsunami and from areas frequently exposed to tsunami risk in active margins such as in Japan. Therefore, disaster protection function or know-how in “tsunami-advanced” nations cannot be adapted directly to the Maldives. The forerunning phenomena, hazardous locations and effective refuge activities described in this study may help with the construction of a disaster prevention program for the Maldives.

Many of the tsunamis recorded in the Indian Ocean originated from seismically active Indonesia (Berninghausen, 1966; Rastogi, 2007). To consider future tsunami prevention in the Maldives, the many facts determined for the 2004 Indian Ocean Tsunami from the east, including variation in disaster status and movement of the tsunami at atolls and islands, will be of value.

For the future, preventive measures such as the construction of safe refuges of solid, high structure and strong walls are necessary. The construction of buffer areas along the coastal zone facing the ocean also should be considered. From the accounts of local residents about places of refuge, it seems that branched trees were especially effective, and the planting of trees such as guava and bread fruit in house yards may be useful for human disaster reduction.

A disaster tends to be easily forgotten with time and the tsunami is gradually becoming a distant memory for Maldivian people. To improve disaster reduction activities, the tsunami story must be kept alive through education of the citizens. The development of educational material on the Indian Ocean Tsunami in the Dhivehi language may help to retain the populations’ awareness of the risk of tsunamis for the future. It is also desirable to disseminate scientific results to the affected local communities through an awareness program. This may create a cultural background to remember the disaster.

The 2004 Indian Ocean tsunami disaster in the Maldives suggests a potential risk for all atoll nations/districts in the Pacific and Indian Oceans. Knowledge of the events of such previous disasters may help us form a basis for recognizing the safer areas of land on atoll islands. The impact of a tsunami differs according to atoll and island topography and, as such, the geomorphological situation should be considered when developing risk management capabilities against tsunamis in atoll nations.

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ERRATA TO:

THE 2004 INDIAN OCEAN TSUNAMI IN THE MALDIVES: SCALE OF THE DISASTER AND TOPOGRAPHIC EFFECTS ON ATOLL REEFS AND ISLANDS

HIRONOBU KAN[1], MOHAMED ALI[2] and MAHMOOD RIYAZ[3,4]

Atoll Research Bulletin No.554 (2007), pp. 1-65

The authors regret the lack of Figure 28 and 29, and Photo 9 in the online publication of the article. These figures and photograph should be placed in page 26.

In addition, the sentence describing the height of coconut forest at Kadoodhoo, Thaa Atoll (page 39, line 34) should have read as follows: Coconut forest at the western part lies on a surface at a height of 0.6-to-0.7m above MSL.

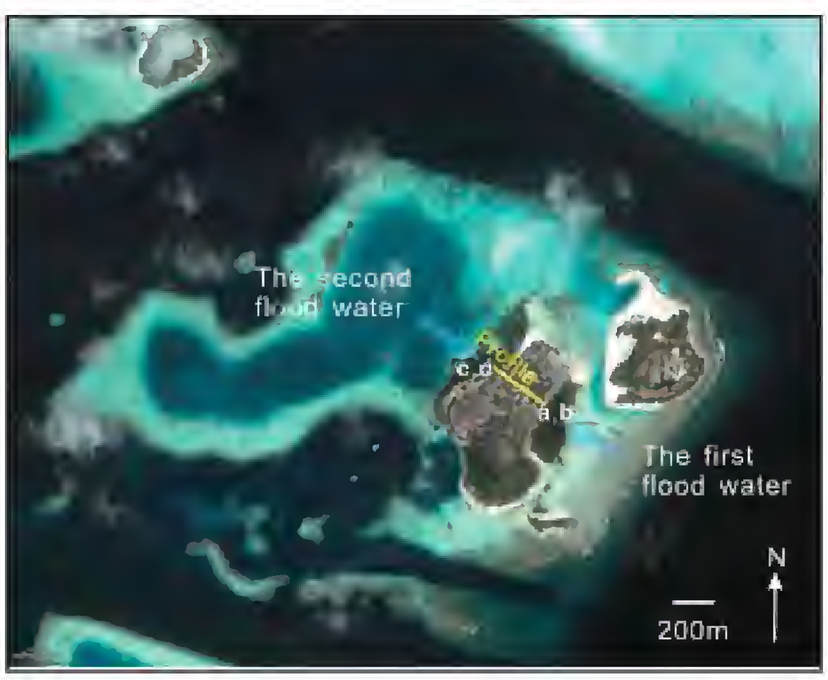

Figure 28. Location of transect and photographic site at Guraidhoo, Kaafu (South Malé Atoll). The satellite image (January 2, 2005) is provided by Digital Globe. a-d: photographic sites for Photo 9.

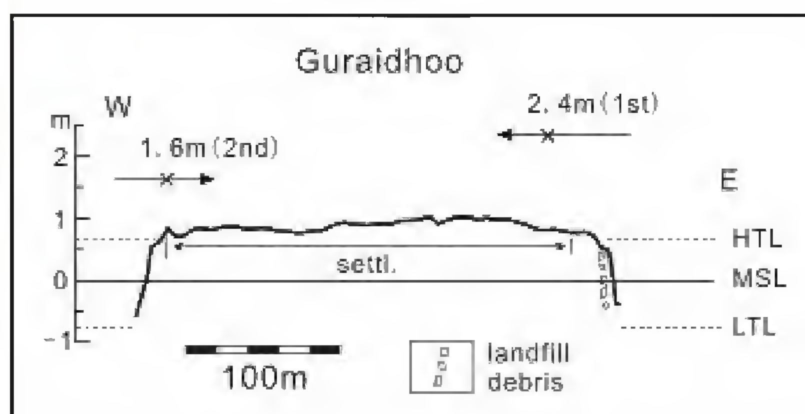

Figure 29. E-W profile of Guraidhoo (see Figure 28 for location). X: watermark, MSL: mean sea level, HTL: highest tide level, LTL: lowest tide level, settl: settlement.

[1] Laboratory of Physical Geography, Graduate School of Education, Okayama University, 3-1-1 Tsushima-Naka, Kita-ku, Okayama 700-8530, Japan. email: kan@cc.okayama-u.ac.jp
[2] SAARC Coastal Zone Management Centre, Jamaaludheen Building, Malé, Republic of Maldives
[3] Environment Research Centre, Jamaaludheen Building, Malé, Republic of Maldives
[4] Geotechnical and Geoenvironmental Engineering, School of Engineering and Technology, Asian Institute of Technology, P.O. Box 4 Klong Luang, Pathumthani 12120, Thailand

Photo 9. Post-tsunami photographs of Guraidhoo (February 2005). a: settlement area completely destroyed at the eastern coast; b: watermark in the living room of the easternmost house; c: dhoni run up at the western coast; d: destroyed wall at the western coast.